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Influence of Different Rubber Modified Binder Variables on Performance Properties of Porous Asphalt Mixtures

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INFLUENCE OF DIFFERENT RUBBER MODIFIED BINDER VARIABLES ON PERFORMANCE PROPERTIES OF POROUS ASPHALT MIXTURES

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ABSTRACT

Porous asphalt is a type of pavement in which surface water can permeate down into the subbase below. Open graded friction course (OGFC) is a type of porous asphalt often used as a surface course on top of dense graded pavements on high speed roadways. Due to an increase in waste tires, rubber modified asphalt has become an increasingly popular material around the world, including the US. The rubber modified asphalt is created by utilizing processed rubber particles blended into the mixture. This research investigated the effects of rubber modified binder on the performance of porous asphalt by evaluating the porosity, permeability, long term draindown, abrasion resistance, fatigue resistance and dynamic modulus. The variables of this research included tire type (passenger and truck tire), crumb rubber processing method (ambient and cryogenic processing) as well as rubber modified blending method (low shear and high shear blending) for a total of eight experimental mixes that were compared to mixtures prepared with typical styrene-butadiene-styrene (SBS) modified binders.

To ensure that the rubber modified binders were of similar quality to the control SBS binder (PG 76-22), DSR testing was performed on varying rubber contents of each binder to find the true failure temperature and G*/sin(δ). The results were then compared to the control binder. The rubber contents selected matched the PG 76-22 true failure temperature and G*/sin(δ) values The optimum binder content was also considered to create comparable mixes. All rubber modified mixtures were mixed using 7.0% binder by weight of the batch. The control mix of PG 76-22 was mixed with 5.5% binder while PG 76-22 with fibers used 7.5% asphalt binder. This variability in the control mixes were necessary due to optimum binder and draindown test standards.

This investigation found that mixtures made with truck tire rubber generally performed better in porosity, initial permeability and provided stable long-term draindown results when compared to passenger car tire rubber. Ambient rubber yielded more desirable results in initial permeability than cryogenic rubber. Overall, high shear and low shear blending gave similar results. With the use of these results, different rubber modified binders can be selected to meet desired performance properties. These results also showed that rubber can be used to replace cellulose fibers in porous asphalt.

DEDICATION

I would like to dedicate this work to my family. First off I need to mention my dad. He has pushed me to work hard and give it my best. My dad has inspired me to be the best person I can be. He has always had my best interest in mind and given me unwavering support through everything. My mom has gone above and beyond to try and keep me living a normal life through all the stress and chaos. She made every trip home special and I will remember those times. My wise grandparents were always there for advice in the times I needed it the most. John always gave me his honest opinion, a trait that I have fully embraced. Robbie Sue's temper continues to teach me how the power of calmness and gentleness can influence everyone. Leonard has lead by example, teaching hard work pays off in the end. Peggy has always kept me positive with all the encouragement which comes from her love for family. Marvin has pushed me to think outside of the box and be willing to take risks. And last, but certainly not least, Jackie has encouraged me, treated me as her own, and always provided laughter and joy. I love all of you and appreciate everything you have done for me because you made me who I am.

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To the Asphalt Rubber Technology Service (ARTS) of Clemson University for providing financial support of this research. I would like to thank all the employees that helped in this research, especially Brookes Lawton and Corinne Lawler.

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CHAPTER 1
INTRODUCTION

Porous pavement is an asphalt mixture that was developed to improve road safety and has also begun to have appeal for the green movement. The mixture has a higher air void content due to reduced fines, which in turn allows water to penetrate through a porous asphalt layer. Typical asphalt pavements are impervious, but porous pavements allow the water to drain from the surface down into a stone recharge bed and infiltrate into the soils below the pavement (Tappeiner 1993). Impervious pavements do not allow water to penetrate the surface, which allows water to collect on the pavement surface creating the potential for hydroplaning. The ability for water to pass through the surface creates a dry road for motorists where the hydroplaning effect is significantly reduced and the roads are safer. Porous asphalt is a green alternative for its benefits seen in stormwater management and water quality. By implementing a porous asphalt pavement in a project, it can eliminate the need for detention ponds. Although there has been limited sampling data, porous pavements are suspected to purify water by removing total suspended solids, metals, oil and grease at very high removal rates before it reaches the soil (Tappeiner 1993). A type of porous asphalt, open graded friction course (OGFC) is often used as a surface layer. Porous asphalt can be expensive in some cases, but by using OFGC as a surface layer it can keep the project cost effective while still attaining the benefits from porous asphalt. OGFC has been investigated in the US since the 1970's and has been modified several times. Since the creation of porous asphalt, many improvements have been made and it continues to evolve.

Problem Statement

Although porous asphalt can improve safety and environmental issues, there are some potential problems that need to be addressed when designing porous asphalt mixtures and pavements. The issues arise in pavement performance with respect to clogging, raveling, cracking and rutting as well as when maintenance is neglected. Clogging can occur when maintenance is not implemented and proper precautions are not considered. Sand and other debris can migrate into the open pores and block the passage of water creating a safety issue by holding water on the surface. The prevention of this happening first involves precautions through design and during construction to keep sediment away from the pavement. Once clogging has occurred, powerful vacuums that can remove the debris from the pavement may be used. Raveling occurs when the binder to aggregate bond is broken as well as the binder cohesion failing allowing aggregate particles to separate from the pavement. This transpires from loss of asphalt binder, exposure to sunlight, traffic frequency, freezing and thawing of the asphalt, mix design, and improper compaction during construction (Porous Pavement 2012). Cracking occurs from repeated traffic loadings. This type of crack implies a structural failure of the pavement. In OGFC, this could also occur due to cracks beneath the surface. Porous asphalt has also had issues arise with rutting resistance in porous pavement applications. Porous asphalt contains a higher binder and air void content allowing for the pavement to compact easier.

One way to improve the performance of porous asphalt is to use rubberized asphalt binder. This modified binder consists of asphalt binder and ground tire rubber (GTR). Ground tire rubber refers to recycled tires which are processed into a crumb rubber material that is used to modify asphalt binder. In the past 20 years the interest in the use of GTR in asphalt binders has increased due to the potential of improving the performance of pavement as well as saving resources (Sun and Li 2010). Although most think that all tires are of the same composition, passenger car tires and truck tires vary in their makeup. This difference in composition could affect the performance of mixtures made with rubber modified binders. Another issue which needs to be investigated is the blending method for the rubber modified binder. Previously, low shear blending has been used for rubber modified binders, however, high shear blending has become more popular.

Research Objectives and Scope

The primary objective of this research was to investigate the influence of different GTR modified binder factors on the performance of porous asphalt mixtures. To accomplish this objective the following tasks were completed:

1. Determine GTR binder formula to obtain the same continuous grade as the control styrene-butadiene-styrene (SBS) modified PG 76-22 binder. This was completed for both passenger car tires and truck tires processed using ambient shredding and cryogenic grinding processing methods. These crumb rubber materials were then blended with asphalt binder using low shear and high shear methods. This resulted in a total of eight different GTR modified binders.
2. Determine the optimum binder content and develop draindown curves for each GTR mix and two control mixtures (one with cellulose fiber and one without).
3. Determine the influence of the different GTR binders on performance properties of the porous asphalt mixtures including porosity, permeability, long-term draindown, raveling susceptibility, fatigue resistance, and dynamic modulus.

Organization of Thesis

This thesis is divided into five chapters. Chapter 1 is an introduction and provides some background information on the research topic of rubber modified asphalt as well as the problem statement and the research objectives. The second chapter includes a literature review, which provides more background information on the topics of OGFC, porous asphalt and rubber modified asphalt. Chapter 3 describes the experimental materials and methods used to complete the individual phases of the research. The fourth chapter presents and discusses the results of this research. The fifth chapter provides a summary of the research, discussion of the conclusions and presents recommendations for further research.

CHAPTER 2
LITERATURE REVIEW

History of Porous Asphalt and OGFC

Porous asphalt is a bituminous mix which has more air voids than dense graded asphalt. A standard porous asphalt contains about 22% voids after compaction in comparison to about 7% for conventional asphalt (Van Heystraeten and Moraux 1990). These additional voids create a network of open space that allows water to penetrate through. Using an open-graded mixture with little fines allows water to migrate down to a deep base of large crushed stones (Field et al. 1982). This water then is absorbed into the subbase below or routed to an underground storage area. While the design and performance of the porous asphalt is very important, it is only part of the success and the stone base should also be carefully considered. If the stone base becomes clogged with debris then the water would be blocked and would cause the asphalt surface to be submerged. For this reason, a single layer of geotextile filter fabric can be used to separate the stone bed from the underlying subgrade, preventing the movement of fines into the bed (Adams 2003).

Since the 1970's the US has experienced an increase in the use of open-graded friction course (OGFC). OGFC is a thin layer of porous asphalt (typically 19 to 38 mm) placed on top of a dense graded asphalt. OGFC helps create a safer road surface for users by increasing the friction coefficient, eliminating hydroplaning, and reducing night time glare. Since the creation of OGFC, there have been varying opinions on the performance of the mix, but there are many locations that have had success. A survey conducted by Mallick et al. (2000) indicated that 80% of states using OGFC have standard specifications for the design and construction. To achieve success with OGFC, careful consideration must be taken in the mixture design phase and, even more importantly, the construction. While some states may have success on heavy traffic highways, it can also be considered for parking lots. OGFC can provide a cost-effective solution compared to completely repaving an area as well as providing stormwater management systems that promote infiltration into the soil, improve water quality, and eliminate the need for a gutters (Cahill et al. 2006). Porous asphalt can significantly benefit the safety and environmental aspects of asphalt surfaces and provide a service life of 10-12 years (Hagos 2002).

Benefits of Porous Asphalt and OGFC

The benefits of using porous asphalt are primarily related to the ability of water to flow through the surface. Improved safety in all types of weather conditions can be seen through use of porous asphalt (Tappeiner 1993). Porous asphalt is a special-purpose mix used to improve friction, minimize hydroplaning, reduce splash and spray, improve night visibility, and lower pavement noise levels (Cooley et al. 2000). Permeability of the asphalt helps eliminate issues with water. The voids in the pavement actually act as a buffer and absorb air inside the pavement removing the slapping sound of air being pressed on a flat surface like conventional asphalt, thus reducing highway related noise.

As stated in 2003, developments create new impervious surfaces and two-thirds of them are related to the automobile (Adams 2003). When put in that perspective, one realizes that there needs to be a countermeasure to balance the equation. The whole watershed is effected every time a new parking lot is paved or road widened. To help offset the effects on the environment, porous pavements can be used as a viable stormwater management technique that can be used on parking lots and low volume roadways to reduce both stormwater runoff volume and pollution (Field et al. 1982). Legret and Colandini reported that porous asphalt filters water remarkably well. A sampling operation of materials carried out on porous pavements have confirmed the accumulation of metals in the porous asphalt and the absence of soil contamination under the reservoir structure (Legret and Colandini 1990).

Issues with Porous Asphalt and OGFC

While porous asphalt is a viable solution for stormwater management, there have been issues. Issues that have arisen include draindown, stripping, raveling, clogging and winter maintenance. Some states simply do not use porous asphalt based on the performance issues. Although the National Center for Asphalt Technology (NCAT) released a mix design for OGFC, the mix does not always work in certain climates. Extremely hot and cold conditions can prove to be detrimental to the asphalt if the conditions are not considered.

Draindown occurs when binder creeps to the bottom of the pavement. This can actually create a completely impermeable surface at the bottom of the asphalt, not allowing water to pass. In turn, the water would begin to submerge the asphalt under water causing many safety issues. Belgian studies reported local problems with draindown by gravity during mixing transport and construction (Decoene 1990). Although this would not completely stop draindown of the binder within loose mix or aged asphalt, cellulouse fibers could be used as a solution to preventing some of the problem.

Millick et al. (2000) found that one major problem associated with OGFC is stripping in underlying asphalt courses. Stripping occurs when the binder to aggregate bond is jeopardized by the introduction of water. Porous asphalt allows water to flow straight to layers beneath and creates a perfect situation for the water to break the aggregate to binder bond. This issue can also be seen in conventional asphalt. To negate the effects of moisture, hydrated lime, or another anti-stripping additive, is added to asphalt mixtures during the mixing process.

Another issue in porous asphalt is raveling. Raveling is the loss of aggregate which can decrease porous asphalt's ability to have adequate friction reduce the life of a pavement and reduce noise (Mo et al. 2009). Although not the only reason, stripping can lead to raveling. If stripping is addressed in the design of mixture, the chances of raveling occurring is reduced. Raveling can be amplified by repeated traffic as the traction of tires can cause the aggregate particles to detach from the pavement. This increase noise and can lead to potholes in the road.

One issue that has occurred, but can be avoided in many cases is clogging. In the same survey by Mallick et al. (2000) some states stated they experienced significant loss in permeability of OGFC after 2-3 years because of clogging of voids by deicing materials or other debris. Porous asphalt being a permeable surface can easily be clogged by sediment in runoff, improper construction practices involving grading and sand used in winter maintenance practices. Use of sediment barriers during construction can control the runoff onto the road and proper side slopes of the road can prevent sediment from being transported onto the surface. Winter maintenance of porous asphalt requires much more careful consideration than for dense graded asphalt (Noort 1997). Deicing materials can be eliminated as an issue if the trucks use a liquid deicer which does not require the use of sand. However, if clogging does become an issue powerful vacuums can be used to remove most of the debris.

History of Rubber Modified Asphalt

The United States has seen a major increase in transportation since the 1980's. With this expansion came economic benefits, but the environmental impacts were not considered beforehand. Annually in the United States, 299 million tires are disposed (Kiser 2007). These tires take up a large percentage of landfill space for a prolonged time. These tires are not environmentally friendly due to the time it takes for the rubber to decompose naturally. After understanding the problem caused by waste tires, legislative bills were created that required the use of rubber in asphalt (Choubane et al. 1999). After backlash from some states, the bills were withdrawn. However, research efforts have continued to find a beneficial uses of tires and asphalt has been a common application.

Tires consist of synthetic fibers, steel wire and rubber. To begin the recycling process, the bead wire surrounding the tire is removed. The remaining part of the tire is ground using one of several different processes and the steel wire is removed. Tire rubber is processed either at ambient temperatures or cryogenic temperatures. Crackermill and granulator processes consists of shearing tire rubber at ambient temperatures which result in irregular surface rubber particles (West et al. 1998). The cryogenic process begins by submerging the tires in a liquid nitrogen bath and then they are crushed (West et al. 1998). Both processes can produce a desired size and result in GTR that can be used in asphalt.

Once the GTR is of the desired size, it can be incorporated into asphalt through two methods: wet or dry blending. The wet process entails blending rubber particles into hot binder, where the dry process does not introduce rubber until the mixing of hot aggregate and binder. The dry process has a major drawback for the use in nonconventional mix designs thus the wet process is preferred for porous mixtures (Takallou and Saiton 1992). The dry process promotes segregation and clumping of the rubber if the mixing procedure is not properly performed

In the 1960’s Sweden developed a paving system called PlusRide that incorporated large rubber particles into asphalt pavements (Esch 1982). This was one of the first countries to recycle rubber in asphalt pavements. Although the US has not completely adopted the use of rubber in asphalt pavements, Europe has embraced it. The addition of GTR in asphalt mixes is anticipated to improve the binder properties by reducing temperature susceptibility (Jeong et al. 2010). Many countries have experienced excellent performance through the use of GTR and continue to implement its use.

The US has had mixed experiences with the use of GTR. Some results have yielded excellent durability, while others have considered rubber modified asphalt a non-cost-effective option due to the extra cost of adding the rubber. A Florida study found the optimum rubber content to be 10-15% by weight of binder (Choubane et al. 1999). While an Arizona study found that 20% GTR to be optimal when mixed at 190°C for 1 hour (Way 2000).

Benefits of Rubber Modified Asphalt

Research and field testing have yielded several desirable results. Most results show the benefits through performance measures, however, one state that has had great success with rubberized porous asphalt stated using asphalt rubber on I-40 in Flagstaff AZ, saved $18 million in construction and 4 years in construction (Way 2000). This example proves that in the right situation, rubberized porous asphalt can be a cost effective alternative.

Performance benefits seen in both porous asphalt and OGFC include resistance to fatigue, cracking and rutting, resistance to draindown and excellent durability. Several results support how rubber can influence cracking resistnace. In an Arizona field test, a rubberized OGFC layer was reported to be virtually crack free with almost no rutting or maintenance as well as good skid resistance after nine years (Way 2000). Another test showed that a wet blending process was more beneficial than the dry process. Over 10 years, the wet process section showed an improved crack resistance of 1-6% cracked areas compared to 30% cracked area of dry process (Choubane et al. 1999).

Other reports show that rubberized asphalt can actually perform better than virgin asphalt. After 3 years of traffic in France an OFGC pavement, results showed advantages in roughness, permeability and evenness of the rubber modified asphalt compared to virgin asphalt (Sainton 1990). This proves an important safety issue can be improved by the use of rubber. The surface of the pavement is extremely important for driver safety and ability to navigate the road, with better friction and evenness, the driver is safer. In another study in France, a test strip of rubberized porous asphalt on heavy traffic turnpikes exhibited excellent durability after 5 years (Sainton 1990). The placement on a turnpike should speak volumes because turnpikes are subjected to excessive heavy traffic. If a rubberized porous asphalt could withstand that use, it could be utilized in virtually any application.

Issues with Rubber Modified Asphalt

Rubber modified asphalt has resistance from some construction companies. The main reason meaning if rubber is used, after the construction all equipment would need to be cleaned for a new mix without rubber. Another reason for hesitation to use rubber is the unwillingness contractors to be responsible for the pavement if it fails within the promised service life. More reasons for resistance include issues with equipment needs and cost (Sainton 1990). Wear on the equipment is an issue because the addition of rubber may clog parts of machines and, therefore, could affect other mixes and time would have to be spent on cleaning and repairing equipment from rubber modified binder.

Cost of rubber modified asphalt has been a long term reason to not use it. Cost comparisons indicate that rubberized asphalt binder can be up to twice as expensive as normal asphalt binder (Way 2000). Although the initial cost is higher, in the long-term it is actually cheaper. A rubberized OGFC layer is a less expensive alternative to repair existing pavement compared to constructing a new pavement when considering the additional cost to mill the failed pavement (Way 2000).

CHAPTER 3
EXPERIMENTAL MATERIALS AND METHODS

This chapter discusses materials used as well as the procedures followed to fulfill the objectives of this research. The materials used for this research included one crushed granite aggregate source, two asphalt binder grades (PG 64-22 and PG 76-22), cellulose fibers, hydrated lime and ground tire rubber (GTR). This research investigated the effects of three different variables related to crumb rubber: Tire type (passenger car and truck), processing method (ambient shredded and cryogenic ground) and the blending method (high shear and low shear). These three variables resulted in eight rubber modified asphalt mixes that were compared to the control mixes using SBS modified PG 76-22 mixes made with and without cellulose fibers.

This study was divided into two main phases. The goal of the first phase was to determine the amount of GTR needed to increase the true grade of the base binder (PG 64-22) to the true grade of the control SBS modified PG 76-22 binder. Once the GTR modified binder formulations were determined for each of the eight experimental mixtures, the second phase began by determining the optimum binder content (OBC) of each mix that were then verified with draindown testing. Specimens were then made for each mix design and tested to measure the porosity, permeability, raveling resistance, fatigue resistance, and dynamic modulus of each mix.

Aggregate

The aggregate used in this research was a crushed granite obtained from a quarry in the midlands of South Carolina. The physical properties of the aggregate are summarized in Table 3.1. The aggregate was placed in an oven overnight at 105°C and then separated into individual size fractions by mechanically sieving. The individual fractions were then combined with 1% hydrated lime by total weight of aggregate to achieve the gradation shown in Table 3.2 and Figure 3.1 for each specimen.

Table 3.1- Aggregate Properties

Property	Value
Bulk Specific Gravity	2.62
Apparent Specific Gravity	2.65
Bulk Specific Gravity (SSD)	2.63
Absorption	0.4%
Angularity	Subangular
Flat & Elongated Particles	1%
LA Abrasion Loss	26%

Table 3.2- Gradation of Mix

Sieve Size	% Passing
1” (25.40 mm)	100
3/4” (19.05 mm)	99.0
1/2” (12.70 mm)	89.5
3/8” (9.53 mm)	36.1
#4 (4.75 mm)	6.3
#8 (2.38 mm)	1.0
#200 (0.075 mm)	0.0

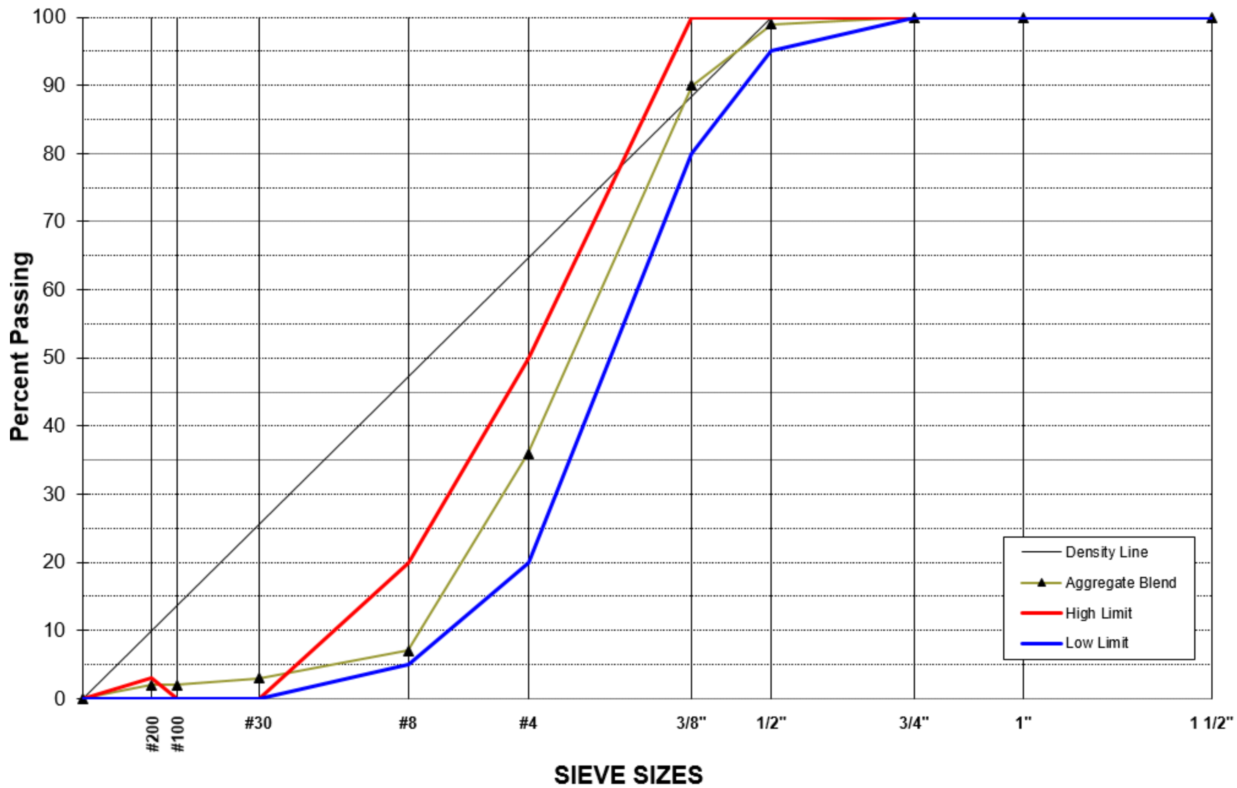
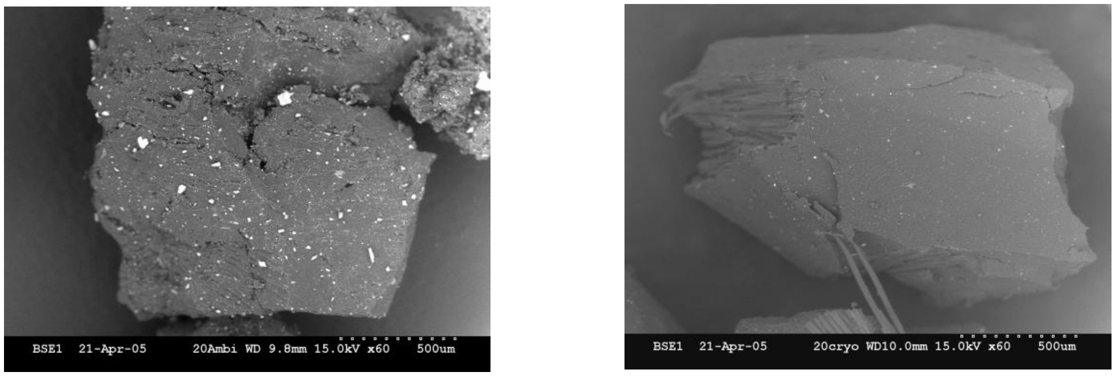


Figure 3.1: Power 0.45 Curve of Mix

<u>Ground Tire Rubber (GTR)</u>

Four different GTR products were used in this project. These GTR products included: Passenger Car Ambient Shredded, Passenger Car Cryogenic Ground, Truck Tire Ambient Shredded, and Truck Tire Cryogenic Ground shown in Figure 3.2. Each GTR had a different particle size distribution, so they were mechanically sieved and divided into individual size fractions before each product was combined to meet the GTR gradation in Table 3.3.



(a) **(b)**

Figure 3.2: Grinding Process Examples: (a) Ambient and (b) Cryogenic

Table 3.3: Combined Gradation of GTR used to Make GTR Binders in this Study

Sieve Size	% Passing
#20 (0.853 mm)	100
#30 (0.599 mm)	92
#40 (0.422 mm)	54
#50 (0.297 mm)	25
#200 (0.0.75 mm)	0

Binder

Two binder grades were used in this research: PG 76-22 and PG 64-22. The binders were sampled from the terminal in 5 gallon buckets. Prior to use, a 5 gallon bucket was heated until the binder was fluid enough to stir which was about 2 hours. The binder was portioned into 1 quart metal cans so each can contained about 600 grams of binder. The exact weight of binder in each can was recorded for blending purposes. The weight of each can was used to determine the exact weight of rubber required. The GTR was added to the base binder (PG 64-22) using 6%, 12%, 18% and in some cases 24% GTR by weight of the binder. The initial step in the blending process was to heat the binder for 90 min or until the temperature reached 170° C. The binder was then placed on a sand bath on top of a hot plate at 182° C. Once the temperature of the binder reached 182° C, the blending process began. Two blending methods were used for the addition of rubber: low-shear and high-shear. The low shear method utilized a mechanical mixer equipped with a high shear radial impeller that rotated at 700 RPM for 30 minutes (Shen et al. 2005). The high-shear machine blended the rubber at 3000 RPM for 1 hour (Billiter et al. 2007). The GTR was added to the binder during blending within the first two minutes. After blending, the binder was sealed labeled and allowed to cool to room temperature. The blending method setups are shown Figure 3.3 and the impellers are shown in Figure 3.4.

(a) (b)

Figure 3.3: Blending Setups (a) Low-Shear and (b) High-Shear

(a) (b)

Figure 3.4: Blending Impellers (a) Low-Shear and (b) High-Shear

Phase 1: Binder

Determination of Ground Tire Rubber (GTR) Content in GTR Modified Binders

Once the GTR modified rubber was prepared, the next step was to determine the percentage of rubber to use for each mix design. The binders were tested following AASHTO T315 using a dynamic shear rheometer (DSR) to determine the original unaged failure temperature based on the G*/sin(δ) values to determine the true performance grade of the binder. The control binder (SBS modified PG 76-22) was tested first to determine its failure temperature. Each GTR modified binder made with the base PG 64-22 binder was then tested in the same manner at varying GTR contents (0, 6, 12, 18, and 24%). The DSR testing started at 64°C and increased in 6°C increments until the binder failed or the test temperature reached 82°C. Each modified binder was then analyzed using the G*/sin(δ) value from the DSR output to determine the GTR percentage which met the failure temperature of the original PG 76-22. The DSR results were graphed with a trend line to calculate the percentage of rubber that met the PG 76-22 failure. The chosen percent for each GTR was then blended and retested in the DSR to verify that it matched the properties of the PG 76-22.

Optimum Binder Content (OBC)

The optimum binder content of each mixture was determined using the SC-T-91 standard which is specifically for open-graded friction course mixtures. Pyrex dishes were filled with 1000 grams of hand mixed, loose asphalt with varying binder contents in 0.5% increments for the different rubber types. The loose mix was placed in an oven at 177°C for two hours, after which the specimen was removed from the oven and carefully placed on a level surface to cool. Once the asphalt was completely cool, the bottoms of the Pyrex dishes were visually inspected to determine which binder content was ideal for the mix design. A mixture below optimum binder content showed few contact points of binder on the bottom of the glass. Beyond the optimum binder content, the contact points connected with each other across the dish, creating a pool of binder. At the optimum binder content, a mix had larger contact points with some connecting to each other, but not so much that pooling occurred (Figure 3.5).

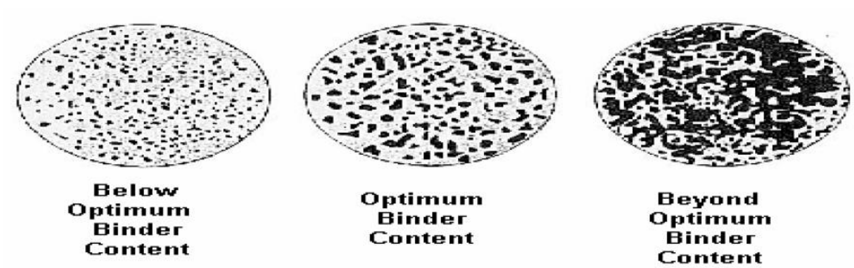


Figure 3.5: Optimum Binder Visual Reference Guide

Draindown

After the optimum binder content was determined, draindown testing was performed following SC-T-90, which is similar to AASHTO T305. Specimens weighing 1200 grams were mixed at the selected OBC, and +/- 0.5% of the OBC. Two specimens for each binder content were hand mixed and placed in 4.75 mm mesh baskets. The baskets were positioned on 20.3 cm diameter pans and placed in an oven at 177°C for three hours. After every hour, the draindown was measured to the nearest 0.1 gram. Once the test was complete, the draindown and optimum binder content results were compared. If the visually selected OBC met the maximum 0.3% draindown by weight of the total mix requirement, it was used as the mix binder content. Equation 1 was used to calculate the draindown.

$$Draindown\ (\%) = \frac{M_i - M_f}{M_t} * 100 \qquad [1]$$

Where:

M_i = Mass of plate before draindown test

M_f = Mass of plate after draindown test

M_t = Total mass of specimen

Phase 2: Mixture Testing

Specimen Preparation

Testing for porosity, permeability, abrasion loss and fatigue resistance required 15 specimens of 150 mm in diameter and of 115 ±5 mm in height. Aggregate batches with 1% hydrated lime, as an anti-stripping agent, were hydrated with water. Water was added at 5% by weight of aggregate and thoroughly mixed by hand. The aggregate was then immediately placed in the oven at the mixing temperature of 157°C overnight. Trial and error was used to determine the aggregate batch weights for these 115 ±5 mm specimens. Binder was slowly heated to the mixing temperature over a period of 3 hours. The dried and heated aggregate was mixed with the binder at the OBC at the mixing temperature. One mix also included cellulose fibers, added by hand and mixed with the aggregate before the binder was added. Fibers were added at a rate of 0.3% by weight of mix. The uncompacted asphalt was placed in a pan with an area of 254 cm^2 and depth of 5.08 cm and then put in another oven at the compaction temperature of 151°C for 2 hours for short term aging. After 2 hours, the loose mix was placed in a 150 mm diameter mold and compacted to a height of 115 ±5 mm in a gyratory compactor using 50 gyrations and a compaction pressure of 600kPa. After compaction, the specimens were carefully extracted from the molds, which took about 10 minutes for each specimen. After being removed from the mold, each specimen was placed on a table at room temperature and allowed to cool in front of a fan overnight before any testing was performed.

Dynamic modulus testing required a specimen core of 100 mm in diameter and a height of 150 mm. To achieve these dimensions, larger specimens were mixed and compacted at the same mixing and compaction temperatures as the 115 mm specimens. These larger specimens were compacted to 170 mm and a trial and error process was utilized until the porosity values were consistently similar to the 115 mm specimens' values. The newly determined aggregate batch weight was then used for the three specimens of each mix design and were mixed and compacted at the same mixing and compaction temperature. Once the specimens cooled overnight with a fan, 100 mm diameter cores were cut using a core drill. The cores were then trimmed on top and bottom to achieve a height of 150 mm using a wet masonry saw with a diamond tipped blade.

Porosity

The porosity of each compacted specimen was measured using the method originally outlined by Montes et al. (2005) and modified by Putman (2012). Before testing, three different measurements of the height and the diameter of each specimen were recorded to the nearest 0.1 mm. The mass of the dry specimen was recorded to the nearest 0.1 gram, then it was submerged in a water bath of 25^{o}C for 30 minutes after which it was flipped upside down under water and tapped 5 times on the bottom of the tank. The specimen was then flipped back to the original orientation on the weigh hook attached to the scale and the submerged mass was recorded. Special care was taken during this test to ensure that the specimen was never in contact with air. The total volume of each specimen was calculated using Equation 2. After the volume was determined, the porosity of each specimen was calculated using Equation 3.

$$V_t = \frac{Davg^2 * Havg * \pi}{4} \quad [2]$$

Where:

D_{avg} = Average diameter of the specimen

H_{avg} = Average height of the specimen

V_t = Total volume

$$Porosity\ (\%) = \left[1 - \left(\frac{\left(\frac{W_{dry} - W_{sub}}{\rho_w}\right)}{V_t}\right)\right] \quad [3]$$

Where:

W_{dry} = Weight of the dry specimen

W_{sub} = Weight of submerged specimen

V_t = Total volume

ρ_w = Density of water at 25^{o}C

Permeability

The permeability of each specimen was measured using the falling head method described by Putman (2012). The test setup, shown in Figure 3.6, included a 15.24 cm diameter tube, a ruler, PVC reduction pieces, a valve and a u-shaped attachment.

Figure 3.6: Permeability Test Apparatus

The specimen was prepared by placing clear 5 cm wide packaging tape which was folded back on itself to the top 2 cm of the specimen and had extra height of at least 1.3 cm above the specimen. Once the tape was on the specimen, the specimen was wrapped with plastic wrap to ensure all the water went through the specimen. The prepared specimen was then placed in the permeameter for testing. The edges of the tape were covered with plumber's putty to ensure all the water was forced through the specimen. The u-shaped outlet was leveled to the same height of the specimen and secured in place. A funnel was used to fill the outlet pipe with water with the valve in the open position. When the outlet was completely full and the specimen fully saturated, the valve was closed and the standpipe was filled with water 38.1 cm above the specimen. Before the valve was opened, the bottom of a ruler was checked to make sure it was at the same level as the height of each individual specimen. Once the valve was opened, a stopwatch was used to measure the time required for the water height to drop 30.5 cm (h_1) above the specimen to 7.6 cm (h_2) above the specimen. The same procedure was repeated three times for each specimen. The permeability was calculated using the average time in Equation 4.

$$Permeability = \frac{aL}{At} ln\left(\frac{h_1}{h_2}\right) \quad [4]$$

Where:

A- Cross-sectional area of the specimen

a- Area of the stand pipe

L- Height of the specimen

t- Time required for water to fall from h_1 to h_2

h_1- Water head at the beginning of the test

h_2- Water head at the end of the test

Long-Term Draindown

The effects of long-term draindown on permeability was investigated using 3 specimens of each mix. The specimens were wrapped with 6.35 mm mesh hardware cloth and secured using steel wire so that the specimens did not slump when exposed to high temperatures. The three specimens were placed on plywood and labeled. Aging was implemented using a dry conditioned room at 60°C for a period of 14 days. After 14 days, the specimens were unwrapped and allowed to cool to room temperature. The specimens were then tested for permeability using the same test method mentioned previously. Each specimen was rewrapped with hardware cloth and placed back into the conditioning room for another 14 days. This process repeated for a total of 8 aging cycles or 112 days.

Abrasion Resistance

Abrasion (raveling) resistance was evaluated using the Cantabro abrasion test in accordance with the method outlined in ASTM D7064. To understand how this property may change over time, three unaged and three aged specimens were tested. Aged specimens were dry conditioned at 60^{o}C for 7 days. Before the test, the initial weight of a specimen was recorded. Both unaged and aged specimens were tested without steel charge in the LA abrasion machine for 300 revolutions. The specimen was then removed from the LA abrasion machine and the final weight was recorded. The percent mass loss was calculated using Equation 5.

$$Loss\ (\%) = \frac{Mi - Mf}{Mi} * 100 \qquad [5]$$

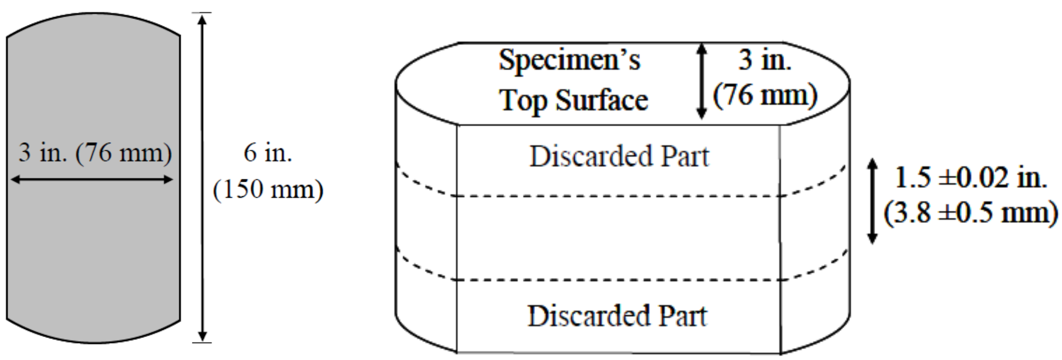
Where:

M_i = Mass of specimen before test

M_f = Mass of specimen after test

Fatigue Resistance

The Texas Overlay Test (TX-248-F) was conducted to determine the susceptibility of each mixture to reflective cracking. For each mix, three unaged and three aged specimens were tested. To age the specimens, they were conditioned at 60°C for seven days. The unaged and aged specimens were trimmed to a 76 mm width, a height of 38 ± 0.5 mm with a length of 150 mm. The dimensions of the trimmed specimen are shown in Figure 3.7. This test was performed using an overlay tester placed in the temperature controlled cell of an Asphalt Mixture Performance Tester (AMPT). The test applied direct tension loads to a specimen for up to 1200 cycles using two separate plates. One of the plates was fixed and the other plate moved vertically 0.6 mm. The machine recorded the load, displacement, and temperature every 10 seconds..



(a) (b)

Figure 3.7: Trimmed Overlay Specimen Dimensions (a) Width and Length and (b) Height

Once the trimmed specimens were dried overnight, a two part epoxy was used to attach the specimen to the two plates. To ensure that the two plates were not affected by the epoxy, a piece of tape was placed between the two plates. The epoxy cured with a 4535.9 g weight on top of the specimen for the required time based on the manufacture's specifications. The plates were then attached to the apparatus and conditioned at 25°C for 1 hour. The test was started using the AMPT controls and continued until a 93% reduction of the original load reading was achieved. If a 93% reduction was not reached, the test was completed to a total of 1200 cycles.

Dynamic Modulus

Dynamic Modulus testing was conducted in accordance with AASHTO TP 79-11 using an AMPT. These specimens were tested for porosity and allowed to completely dry before testing. Three specimens from each mix were tested at the temperatures and frequencies with the initial modulus shown in Table 3.4. Prior to testing, the specimens were conditioned at the test temperature for one hour before placing them into the test chamber. Once in the test chamber the system was allowed to moderate to the correct test temperature which occurred over about 30 minutes.

Table 3.4- Dynamic Modulus Testing Variables

Test Temperature (°C)	Frequency (Hz)	Initial Modulus (kPa)
4.0	10, 1, 0.1	3500
20.0	10, 1, 0.1	1250
45.0	10, 1, 0.1, 0.01	500

CHAPTER 4
RESULTS AND DISCUSSION

In this chapter, the experimental results for the 10 mix designs are presented and discussed. The mixes tested were. First, the experimental binders were formulated based on DSR test results. Each experimental binder was produced to match the true grade of the PG 76-22 control binder. Once the correct rubber content was selected for each mix, uncompacted specimens were prepared to determine the optimum binder content (OBC) and to test the draindown of each mix. Then compacted specimens were prepared to measure the porosity, permeability, Cantabro abrasion, Texas Overlay Test and dynamic modulus.

The experimental results were analyzed using a Student's t-test to detect statically significant differences between treatments. This analysis was conducted at a 95% level of significance ($\alpha = 0.05$). These results are presented in the following sections as a connecting letters report to simplify the comparisons. When interpreting a connecting letters report, if two results both have letter 'A' then they are statistically similar. If one results has a 'A' and another a "B' then they are statistically different.

The results were also analyzed to determine what effect each research variable had on the outcome. This was done using the same statistical test except each variable was compared to each other as a whole. For example results of PC Amb Low, PC Amb High, PC Cryo Low, PC Cryo High, TT Amb Low, TT Amb High, TT Cryo Low and TT Cryo High were combined to create one PC mix and one TT mix to compare statistically to each other.

Phase 1: Binder

DSR Testing

The DSR was utilized to initiate the experiment by completing a SHRP grade determination of the PG 76-22 binder starting at 64°C. Although binders are categorized using a grade system, the true properties of binders of the same grade (e.g., PG 76-22) may not be the same at a given temperature. Thus this testing was completed to create rubber modified binders having the same binder properties to allow for more accurate comparisons to be made. The results yielded a failure temperature for the control SBS modified PG 76-22 binder of 79.9°C and a G*/sinδ value of 1.435 kPa at 76°C. These values were used to compare the results of the modified binders using PC rubber shown in Figures 4.1 and 4.2 and using TT rubber in Figure 4.3 and 4.4. Both control values were used to find the rubber percentage required to have a failure temperature of 79.9°C. The target rubber content was selected to the next highest 0.5% increment.

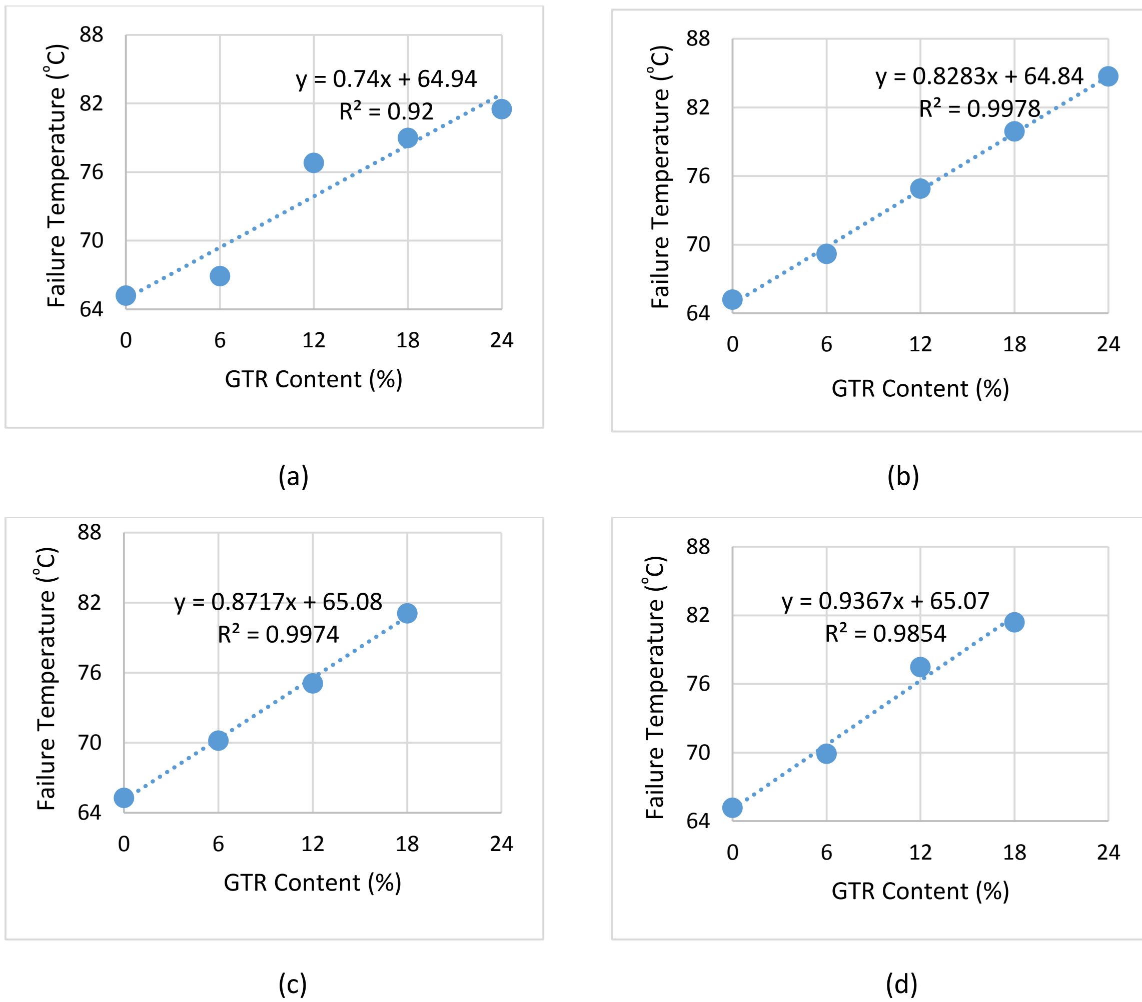
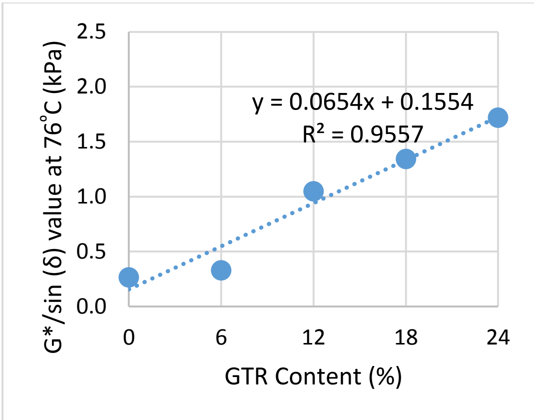


Figure 4.1 - DSR Failure Temperatures for PC Mix
(a) Amb Low, (b) Amb High, (c) Cryo Low and (d) Cryo High



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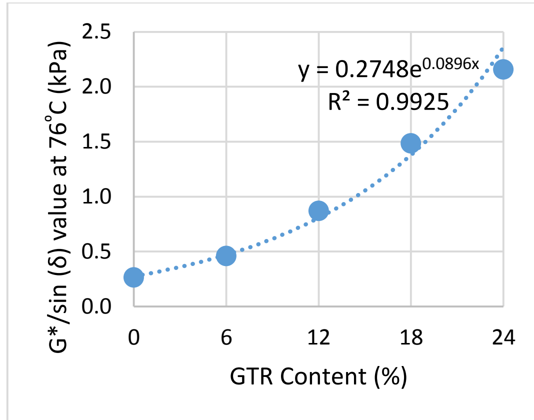

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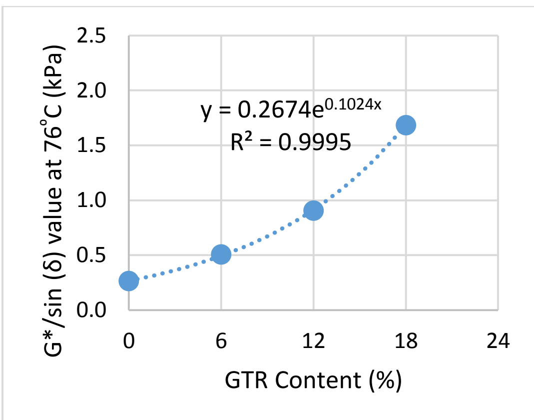

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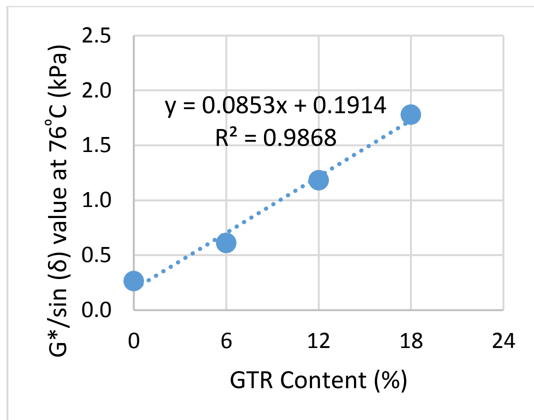


(d)

Figure 4.2 - G*/sin (δ) value at 76°C for PC Mix
(a) Amb Low, (b) Amb High, (c) Cryo Low and (d) Cryo High

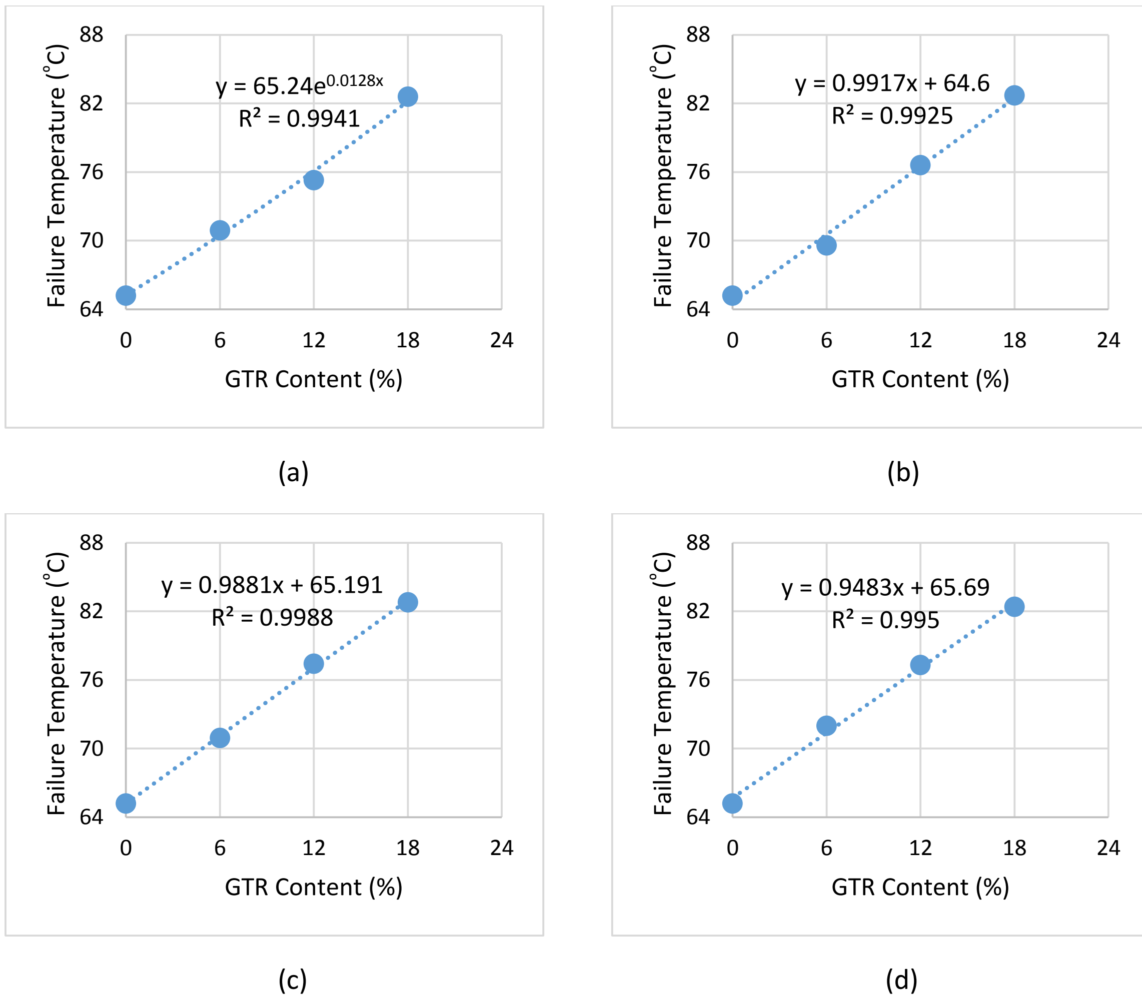


Figure 4.3 - DSR Failure Temperatures for TT Mix
(a) Amb Low, (b) Amb High, (c) Cryo Low and (d) Cryo High

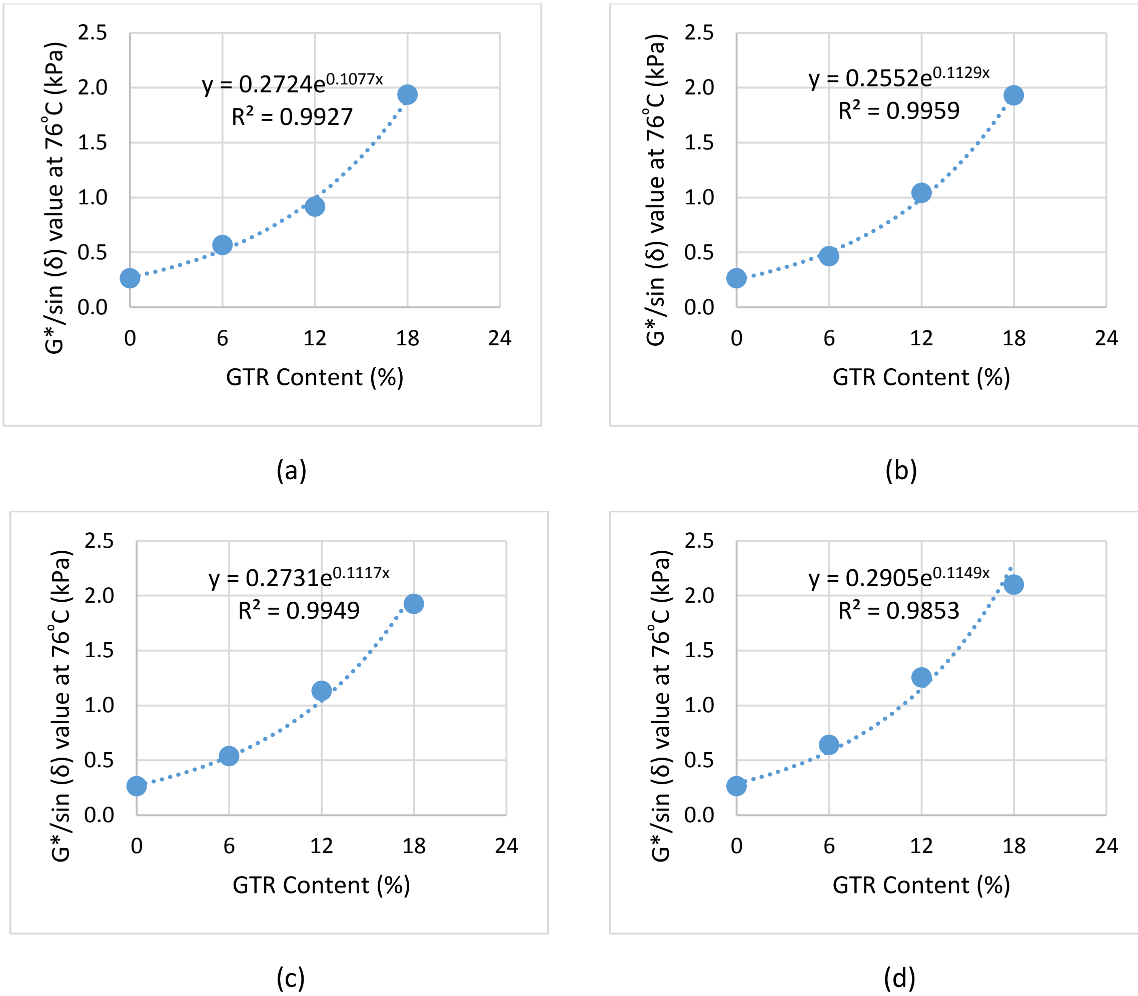


Figure 4.4 - G*/sin (δ) at 76˚C for TT Mix
(a) Amb Low, (b) Amb High, (c) Cryo Low and (d) Cryo High

Using the information in Figures 4.1 through 4.4, a rubber content was selected for each experimental binder. Binders made with this rubber content were then tested to verify that they closely matched the properties of the control PG 76-22 binder. These verifications are shown in Table 4.1.

Table 4.1 Final Rubber Modified Binder Test Results

Mix	Rubber Content (%)	Failure Temperature (˚C)	G*/sinδ (kPa)
76	NA	79.9	1.435
76F	NA	79.9	1.435
PC Amb Low	19.5	81.6	1.702
PC Amb High	18.0	81.5	1.694
PC Cryo Low	16.5	80.1	1.542
PC Cryo High	16.0	81.3	1.779
TT Amb Low	16.0	80.5	1.541
TT Amb High	15.5	81.0	1.604
TT Cryo Low	16.0	80.0	1.471
TT Cryo High	15.5	78.6	1.282

The results in Table 4.1 show some differences in GTR content for some of the binders. This could possibly be due to variability in the GTR production. There were four different sources of rubber and each plant may have a different process, feedstock, or additives used to facilitate the production causing the absorption of binder into the rubber to vary.

Optimum Binder Content

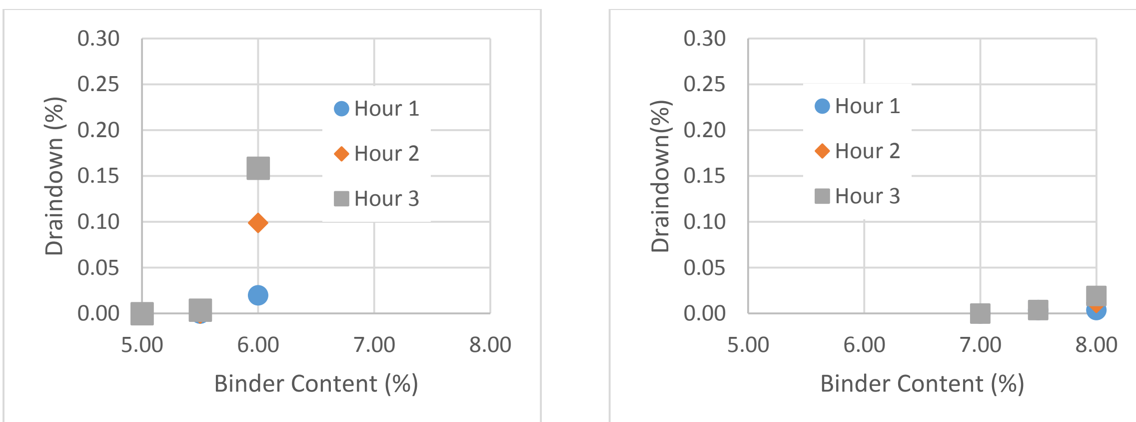
To determine the optimum binder content for the porous asphalt mixes, uncompacted specimens were visually tested in accordance to SC-T-91 as explained in Chapter Three. Six specimens for each mix were produced using three different binder contents (two specimens per binder content). Table 4.1 shows the optimum binder content selected for each mix. Mix 76 had the lowest binder content of 5.5% (by weight of total mix). The highest binder content was found for the 76F, this is due to the inclusion of cellulose fibers that absorb some of the binder. All the rubber modified binders were chosen to have 7.0% binder content. The rubber modified binders have a higher binder content than the 76 and this can be due to absorption of binder components into the rubber particles as well as the filling effect of the rubber particles increasing the binder viscosity. The rubber particles can be considered as a miniature aggregate particle, the high surface area can require a greater amount of binder to maintain adequate adhesion of the asphalt mix. The OBC photos can be seen in Appendix A.

Table 4.2 - Optimum Binder Content of Each Binder Type

Mix	Optimum Binder Content (%)
76	5.5
76F	7.5
PC Amb Low	7.0
PC Amb High	7.0
PC Cryo Low	7.0
PC Cryo High	7.0
TT Amb Low	7.0
TT Amb High	7.0
TT Cryo Low	7.0
TT Cryo High	7.0

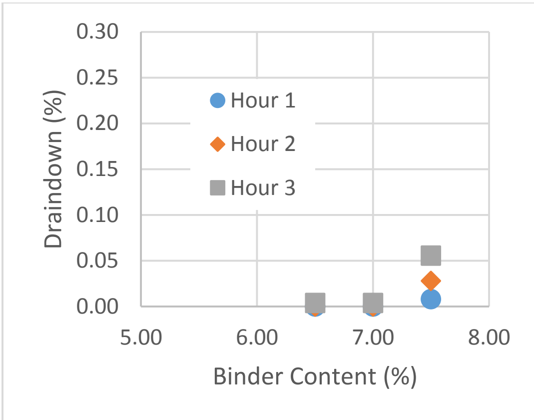
Draindown

Once the OBC was determined, additional testing was completed to assure the percentage of binder would not draindown excessively at high temperatures. Binder draindown testing was completed in accordance with AASHTO T305 for all mixes. The maximum allowable draindown after 1 hour at 177°C is 0.3%, however testing was completed for 3 hours to ensure that the selected binder content would continue to be stable at higher temperatures. Draindown curves for the control mixes are shown in Figure 4.5. The 76 mix had the highest draindown of about 0.15% after 3 hours, however this draindown occurred at a binder content of 6.0%, which was above the selected OBC of 5.5%. The 76-22 mix with fibers (76F) showed a significant resistance to draindown. Figures 4.6 and 4.7 show how the PC rubber and TT rubber mixes, respectively responded to high temperatures. All modified binders performed well, only one specimen of PC Amb Low and TT Cryo High resulted in a draindown of more than 0.05% after 3 hours. The draindown data can be seen in Appendix B.

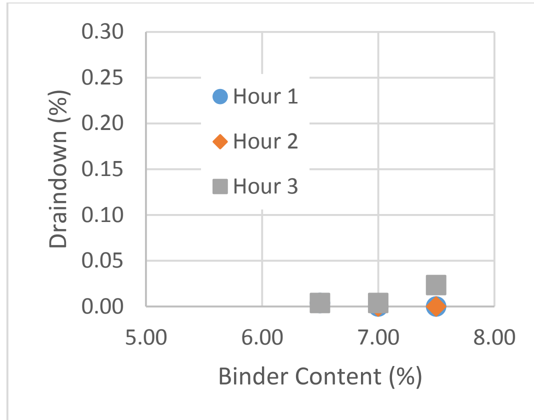


(a) (b)

Figure 4.5 - Control Mix Draindown
(a) 76 (b) 76F



(a)



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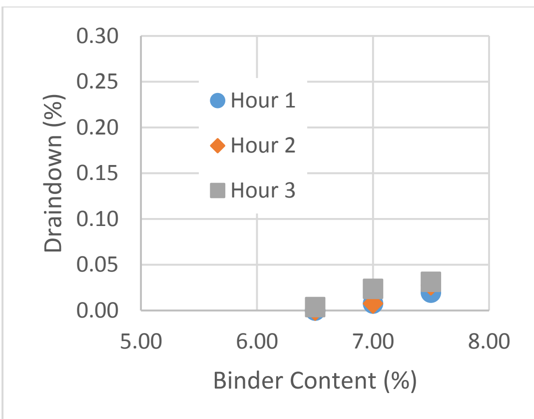

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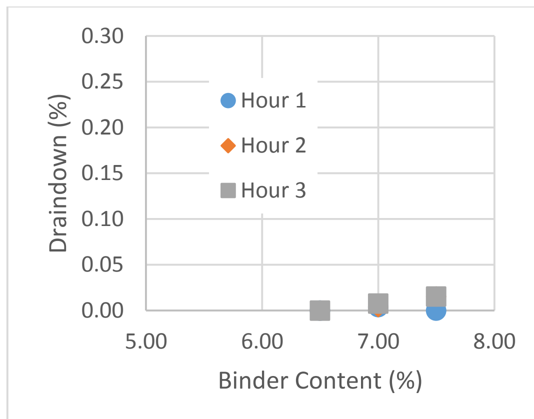


(d)

Figure 4.6 - PC Mix Draindown
(a) Amb Low (b) Amb High (c) Cryo Low (d) Cryo High

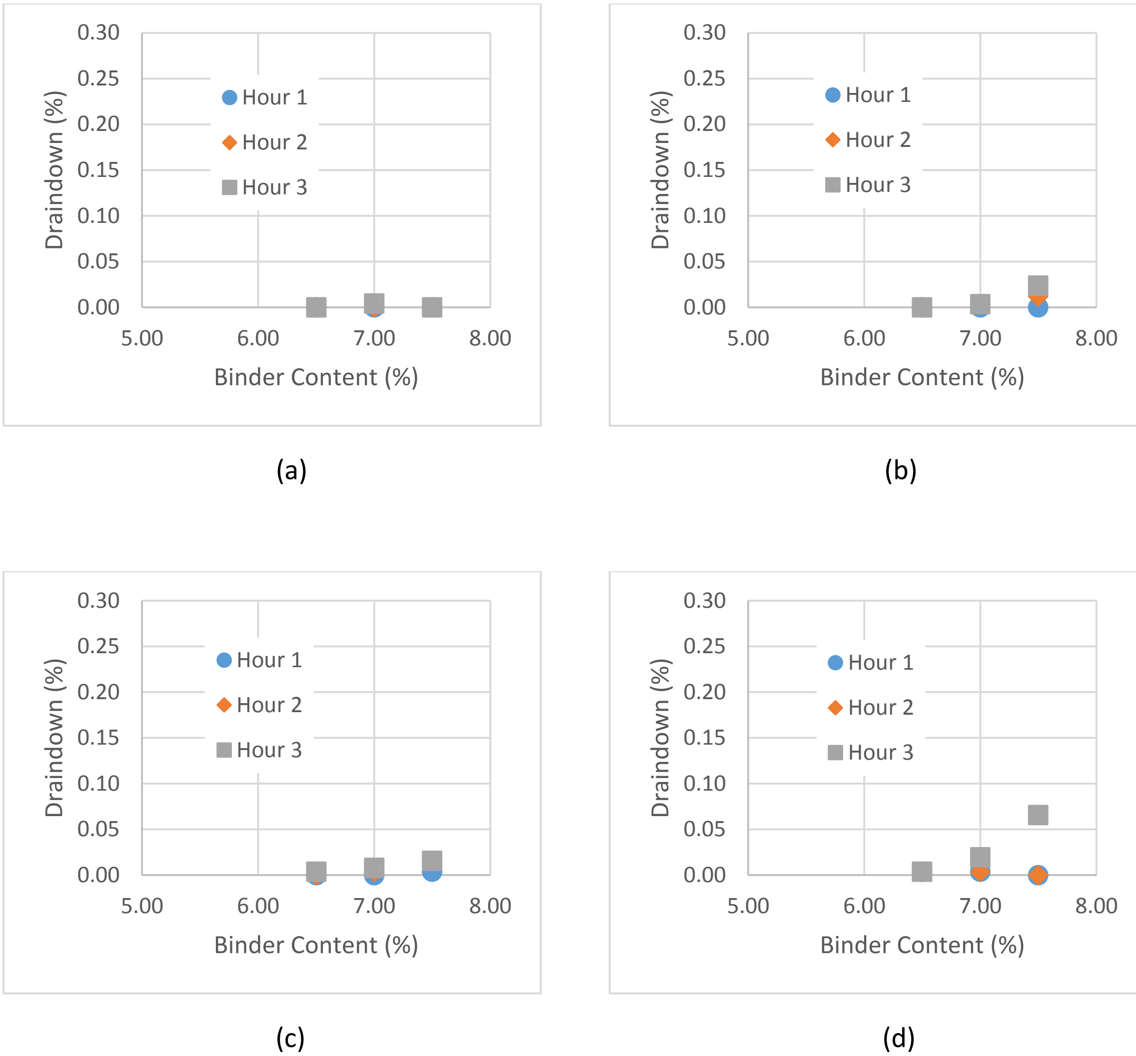


Figure 4.7 - TT Mix Draindown
(a) Amb Low (b) Amb High (c) Cryo Low (d) Cryo High

Phase 2: Mixture Testing

Porosity

Porosity refers to the volume of interconnected voids within a specimen. These connected voids are how water can penetrate and flow through porous asphalt. The porosity of each specimen was determined using the method described in Chapter 3. Figure 4.8 displays the average porosity of each mix along with the standard deviation. From the figure it can be seen that the TT mixes had a significant increase in porosity while the control and PC mixes were relatively similar. The TT mix had the most consistent results. From the average values the Cryo rubber mixes typically had an increase in porosity when the high shear blending method was utilized.

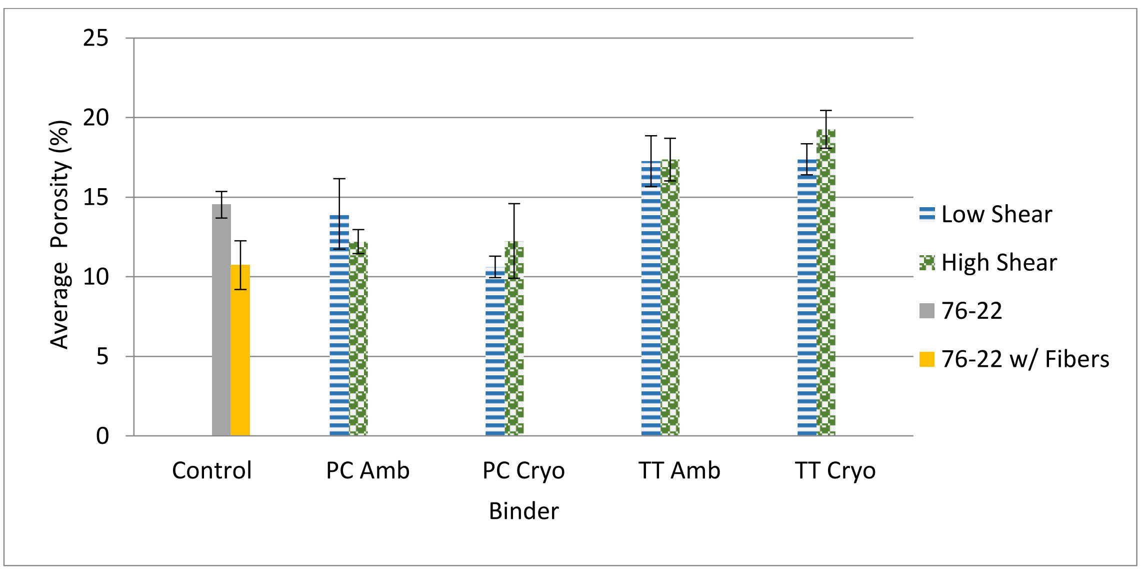


Figure 4.8 - Average Porosity of Each Mix

When comparing the control mixes of 76 and 76F, the fibers caused a decrease in porosity. This can be attributed to the tendency of the fibers to clog and isolate voids so that they are inaccessible to water. The statistical analysis for porosity with the average values are shown in Table 4.3. When comparing the control mixes, they are statistically different. PC Amb High, PC Cryo Low, PC Cryo high and 76F are all statistically similar while PC Amb Low is statistically similar to only PC Amb High, PC Cryo High and 76. The TT mixes were all similar to each other and TT Amb Low was also similar to 76. Table 4.4 shows that the tire type was a significant factor as the cryogenic GTR mixtures had significantly different results from the ambient mixtures. After a closer look, the processing method did not have a significant effect on the results as shown in Table 4.5. In comparing these values, the blending method also did not have an effect on the porosity as seen in Table 4.6. The data for porosity can be found in Appendix C.

Table 4.3 - Statistical Analysis of Difference In Porosity

Mix	Average Porosity (%)	Connecting Letters Report
76	14.5	BC
76F	10.7	E
PC Amb Low	14.0	CD
PC Amb High	12.2	DE
PC Cryo Low	10.6	E
PC Cryo High	12.3	DE
TT Amb Low	17.3	AB
TT Amb High	17.4	A
TT Cryo Low	17.4	A
TT Cryo High	19.3	A

Table 4.4 - Effect of Tire Type on Porosity

Mix	Connecting Letters Report
76	B
76F	D
PC	C
TT	A

Table 4.5 - Effect of Processing Method on Porosity

Mix	Connecting Letters Report
76	AB
76F	B
Amb	A
Cryo	A

Table 4.6 - Effect of Blending Method on Porosity

Mix	Connecting Letters Report
76	AB
76F	B
Low	A
High	A

Permeability

Permeability is the measurement of the rate at which water flows through a porous object. In terms of porous asphalt, this value can be one of the most important properties. Permeability of the specimens was measured using a falling head test described in Chapter 3. Figure 4.9 shows the average permeability of each mix. The 76 mix had the highest initial average permeability and the PC Cryo Low had the lowest result.

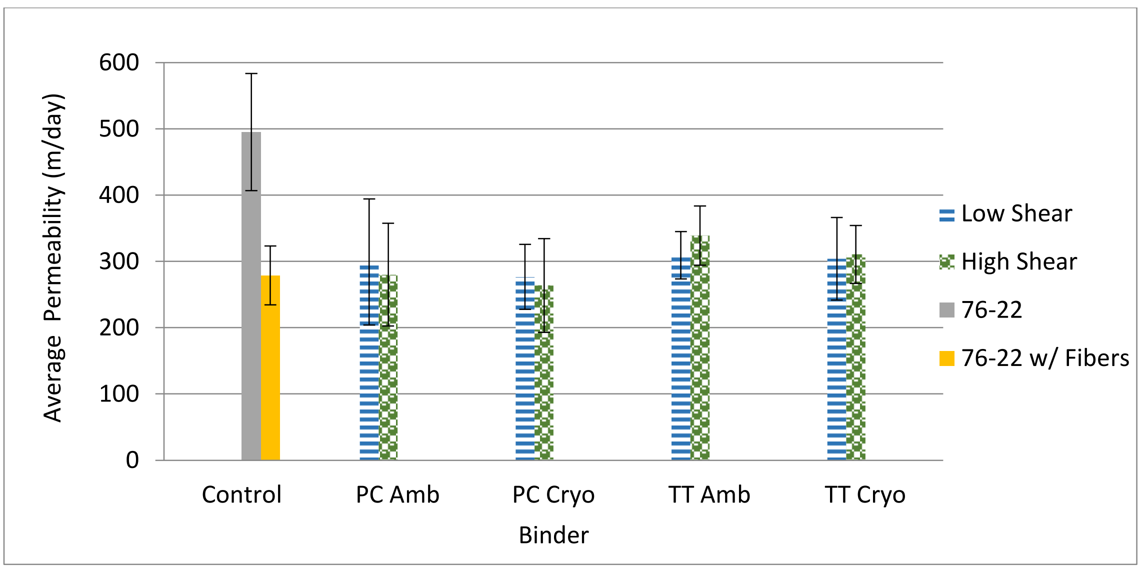


Figure 4.9 - Average Initial Permeability for Each Mix

Table 4.7 summarizes the average permeability and the results of the statistical analysis. The 76 was not statistically similar to any mix. This may be due to the fact that the fibers and the small rubber particles block some of the voids not allowing for water to flow as easily. 76F was similar to all of the GTR mixes except PC Amb High, TT Amb Low and TT Amb High. The TT mixes were similar to each other and PC Amb High. In comparing PC mixes, PC Amb Low, PC Cryo Low and PC Cryo High were similar. PC amb High was similar to only the TT mixes.

Table 4.7 - Statistical Analysis of Initial Permeability

Mix	Average Permeability (m/day)	Connecting Letters Report
76	494	A
76F	278	DE
PC Amb Low	300	CDE
PC Amb High	281	B
PC Cryo Low	276	E
PC Cryo High	264	CDE
TT Amb Low	310	BC
TT Amb High	338	B
TT Cryo Low	305	BCD
TT Cryo High	310	BCD

Tables 4.8, 4.9, and 4.10 provide a simpler breakdown of the three variable effects on permeability results. From the statistical analysis, the tire type and the processing method affected the permeability outcome while the blending method had no effect.

Table 4.8 - Effect of Tire Type on Permeability

Mix	Connecting Letters Report
76	A
76F	BC
PC	C
TT	B

Table 4.9 - Effect of Processing Method on Permeability

Mix	Connecting Letters Report
76	A
76F	BC
Amb	B
Cryo	C

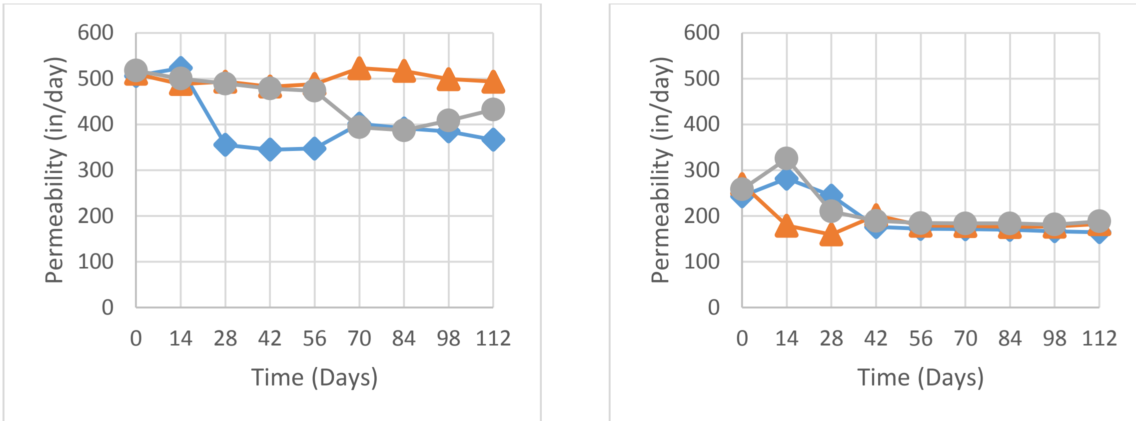
Table 4.10 - Effect of Blending Method on Permeability

Mix	Connecting Letters Report
76	A
76F	B
Low	B
High	B

Long-Term Draindown

Long-term draindown applies to the issue of the behavior of the binder film when exposed to elevated temperatures experienced during service. In the field, old pavements do not behave in the same manner as the new mat once did. Aging occurs from climate conditions and, for porous asphalt, one of the main issues is high temperatures. As temperatures rise, the viscosity of the binder decreases allowing the binder to slowly move to the bottom portion of the asphalt layer under the force of gravity. This could possibly seal the pavement on the bottom. The problem with permeability is that the response of porous asphalt is not well understood over a long-term period of service. This research used artificial conditioning to simulate a weathered pavement specimen.

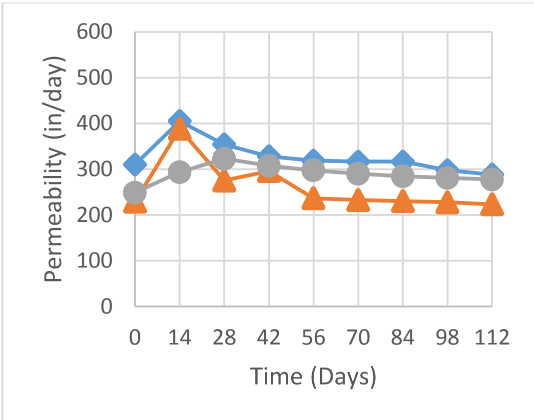
Figure 4.10 shows the aged permeability responses of the control mixes. The 76 mix had a relatively high permeability which ranged for three specimens from 350-620 m/day over the 112 day conditioning period. The permeability of this mix did not level out over time as expected. 76F had a much lower permeability of around 200 m/day. Although this was a lower permeability, it was an acceptable value. After 42 days, the permeability leveled out and there was hardly any change after the time period.



(a) (b)

Figure 4.10 - Long Term Draindown for Control Mix
(a) 76 (b) 76F

Figure 4.11 shows the aged permeability data for the PC mixes. All four of these mixes showed a jump in the first 14 days and then at 28 days, returned to a consistent rate. The PC mixes were all in the 200-400 m/day range which is actually higher than the 76 with fibers mix. This shows that that the rubber modified binder can be beneficial compared to the use of fibers as a stabilizing additive.



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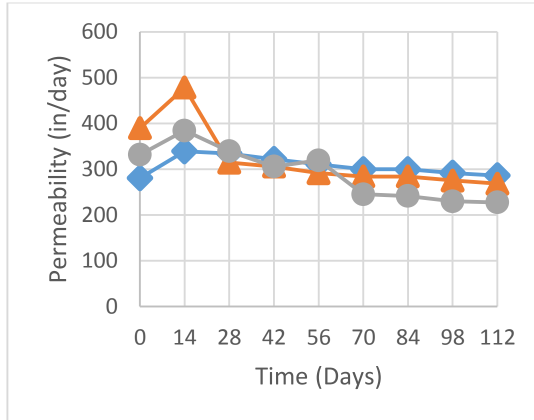

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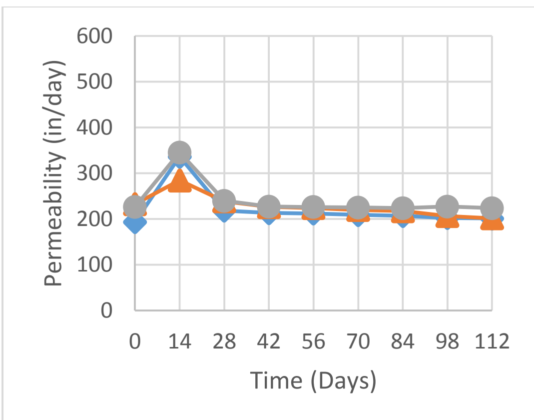

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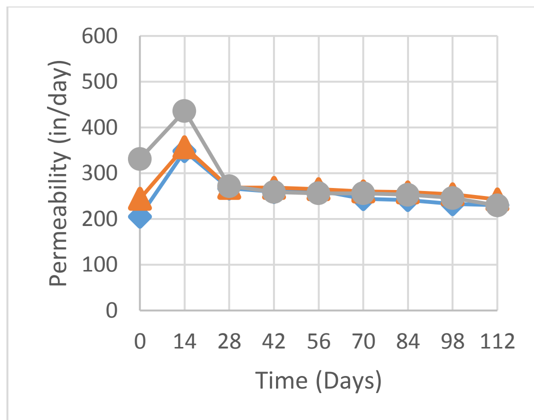


(d)

Figure 4.11 - Long Term Draindown for PC Mix
(a) Amb Low (b) Amb High (c) Cryo Low (d) Cryo High

The TT mixes showed a greater consistency in the results (Figure 4.12). The permeability of the TT mixes was also in the 200-400 m/day range but there was not much of a difference in permeability from the initial reading to that at 112 days. The consistency of the results may be attributed to the chemical makeup of the rubber in TT. The TT and PC mix values were similar and both could replace the use of fibers and increase permeability rates.

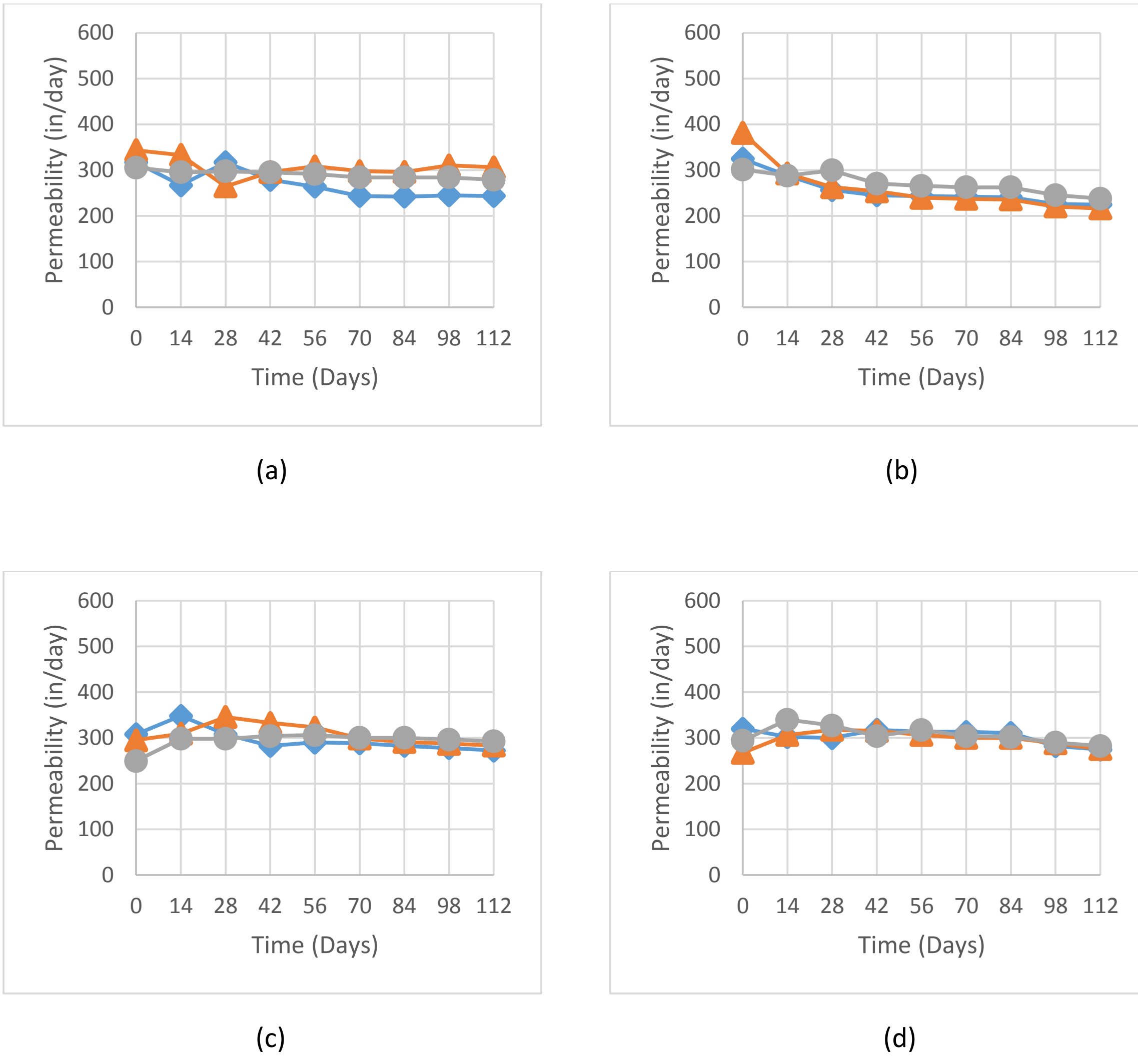
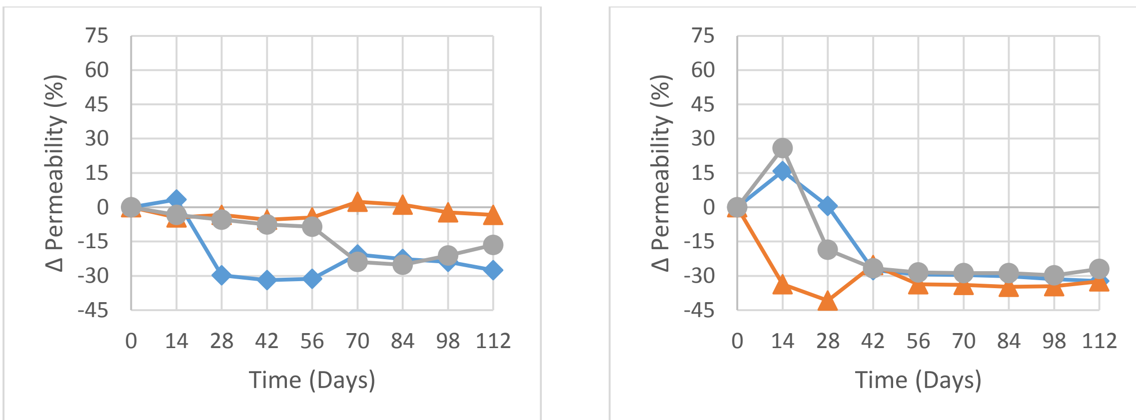


Figure 4.12 - Long Term Draindown for TT Mix
(a) Amb Low (b) Amb High (c) Cryo Low (d) Cryo High

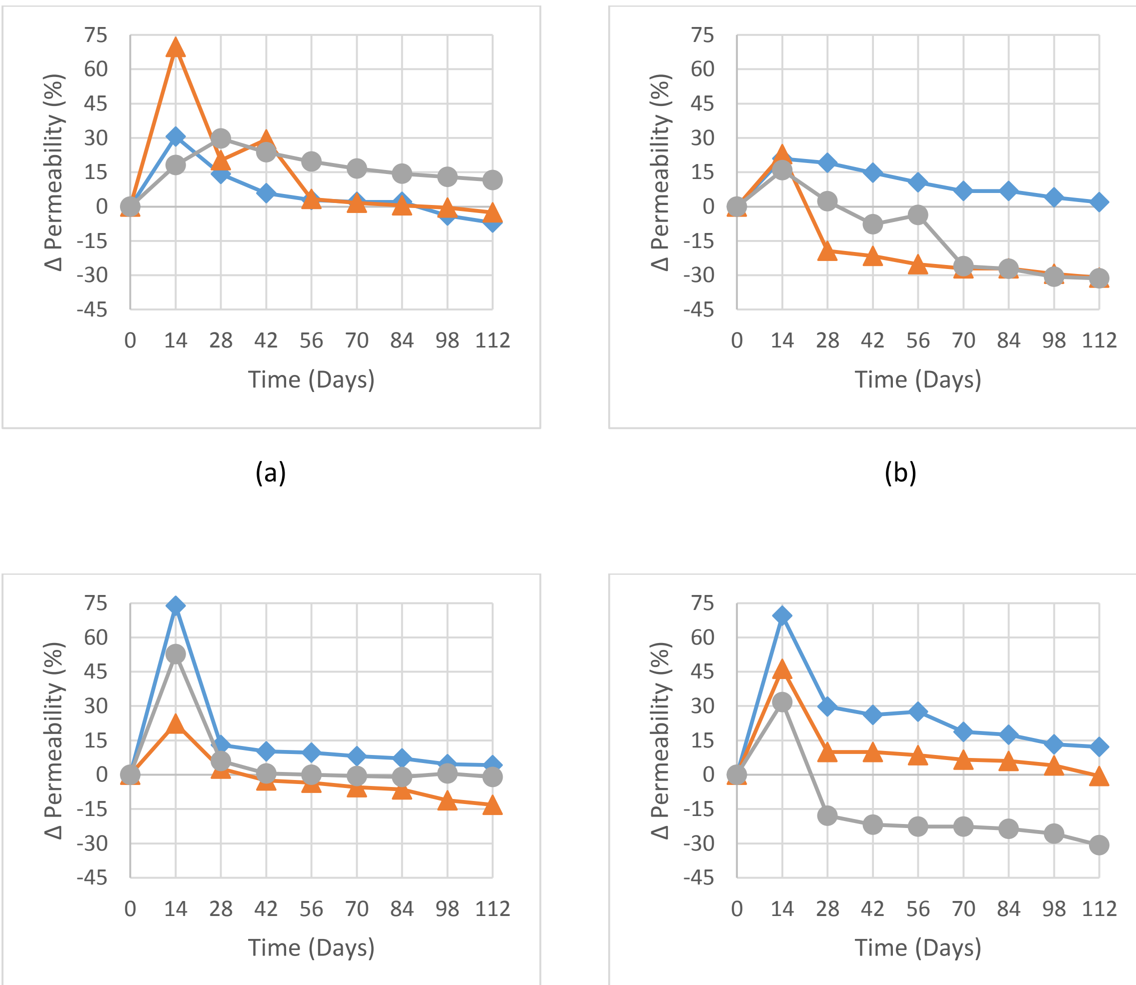
A more in depth analysis was completed on the long-term draindown in terms of understanding how the permeability decreased or fluctuated at each time period with respect to the initial permeability value. In Figure 4.13, the 76 specimens seemed to have an unpredictable change in permeability. While the 76 with fibers showed a trend with two specimens peaking with a change of +30% in permeability and then following a similar fall and flat lined until 112 days.



(a) (b)

Figure 4.13 - Percent Change In Permeability for Control Mix
(a) 76 (b) 76F

Figure 4.14 shows that the Amb rubber had a slightly erratic change and the Cryo rubber followed a consistent trend. The Cryo rubber displayed an interesting increase of almost 74% in permeability in the first 14 days.



(a) (b) (c) (d)

Figure 4.14 - Percent Change In Permeability for PC Mix
(a) Amb Low (b) Amb High (c) Cryo Low (d) Cryo High

The trends in Figure 4.15 show that the TT mixes were fairly stable. The TT Amb Low mix had a maximum change of about -23% at 28 days and at 70 days the results stopped varying. TT Amb High had a constant sweeping decrease in permeability that decreased up to 43%. Both the TT Cryo mixes had a similar shape of the permeability changes—they increased slightly to about 20% and slowly dropped back to around the initial permeability.

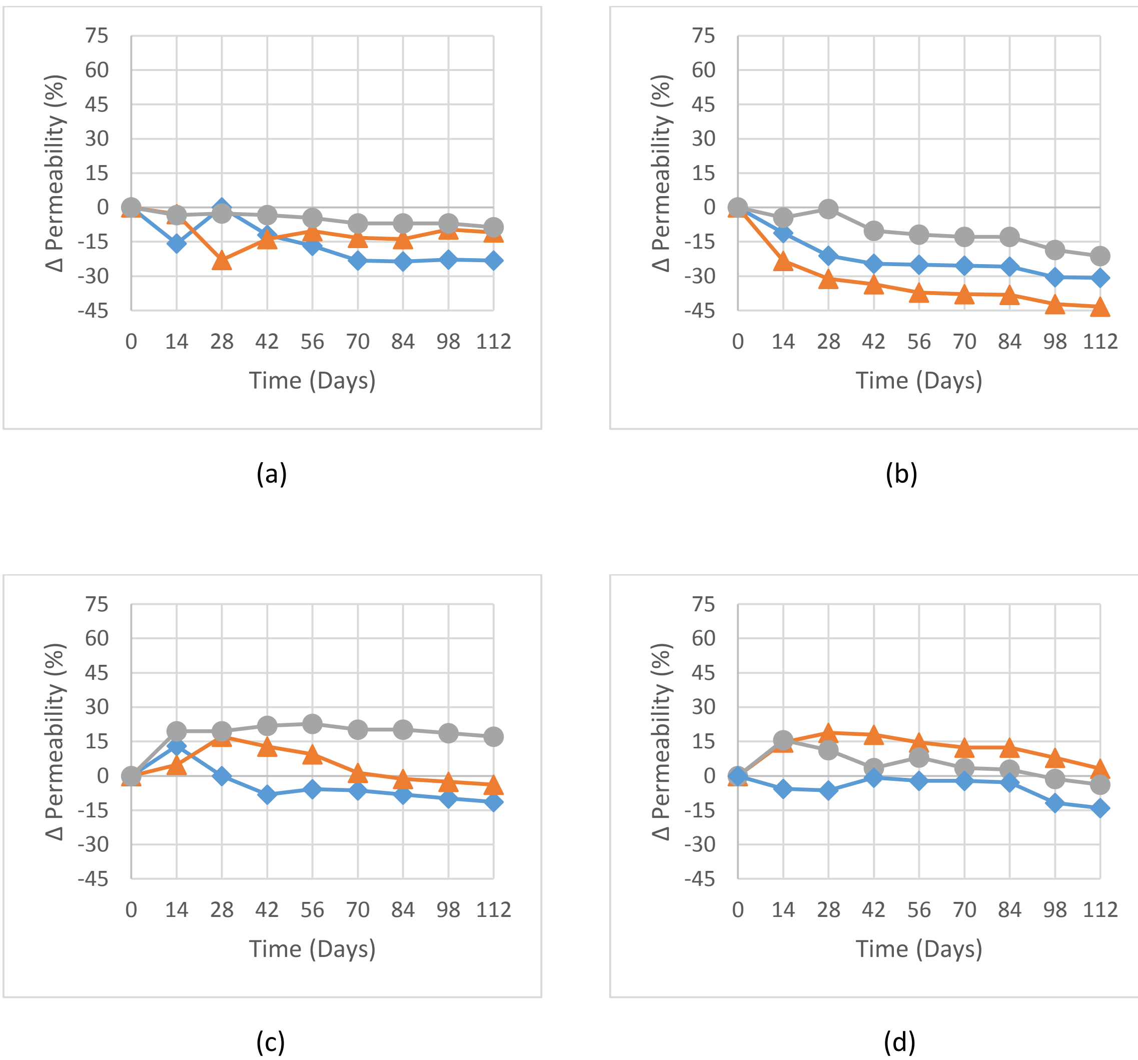
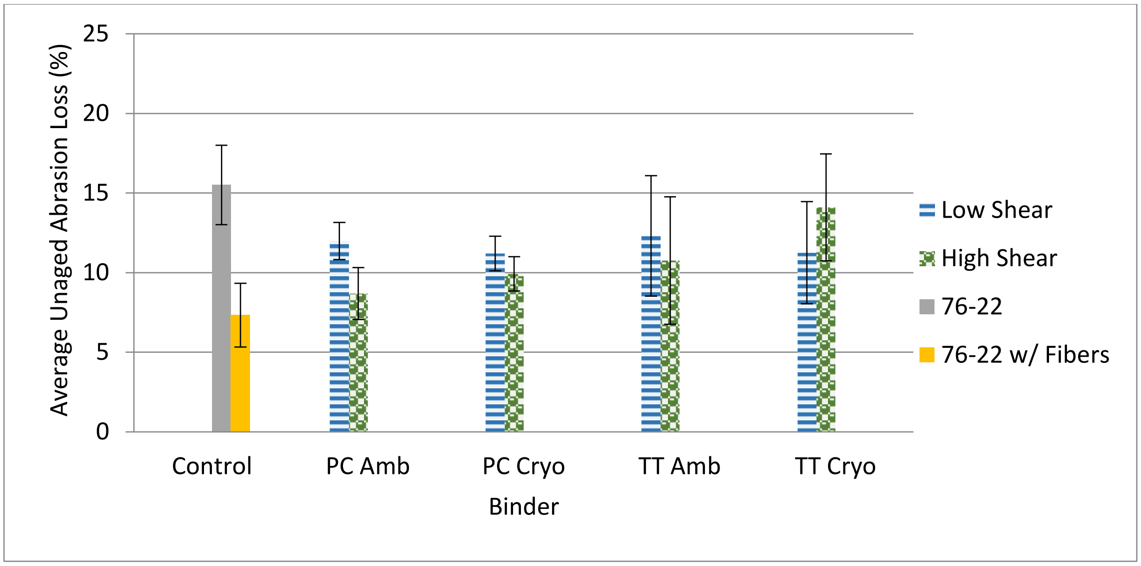


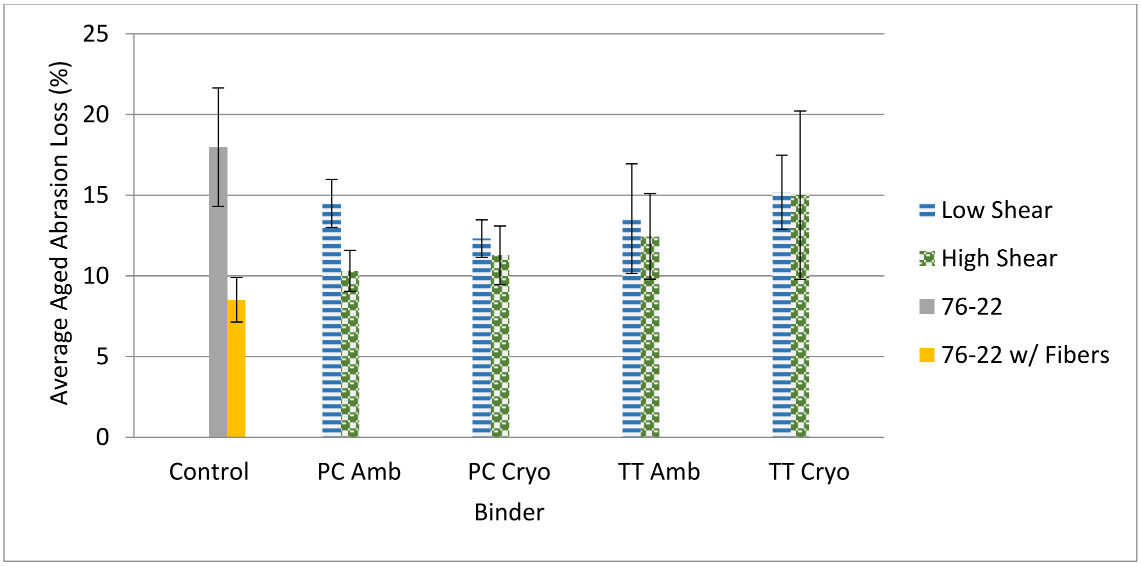
Figure 4.15 - Percent Change In Permeability for TT Mix
(a) Amb Low (b) Amb High (c) Cryo Low (d) Cryo High

Abrasion Resistance

To understand how the mixes would withstand raveling, the Cantabro abrasion test was performed on both unaged and aged specimens. The standard of ASTM D7064 requires that the abrasion loss is not more than 20% for unaged specimens and 30% for aged specimens. It was expected that the aged specimens would have more abrasion loss due to the change in binder properties resulting from high temperature conditioning. When binder is exposed to high temperatures, it oxidizes and becomes brittle and easier to break the binder to aggregate bond within the specimen. It was assumed that the mix with fibers would have the least abrasion loss and the 76 control mix would have the highest loss which can be seen for both the aged and unaged specimens in Figure 4.16.



(a)



(b)

Figure 4.16 - Average Abrasion Loss
(a)Unaged Specimens (b) Aged Specimens

Table 4.11 shows the unaged average abrasion loss and the results of the statistical analysis. The control 76 mix was similar to PC Amb Low, PC Cryo Low, TT Amb Low, TT Cryo Low and TT Cryo High. 76F was similar to all the mixes except 76, PC Amb Low, TT Amb Low and TT Cryo High. The TT and PC mixes were similar to each other. The low shear mixes all shared similar abrasion losses and the high shear mixes were statistically similar to each other except for TT Cryo High.

Table 4.11 - Statistical Analysis of Abrasion Resistance in Unaged Specimens

Mix	Average Unaged Abrasion Loss (%)	Connecting Letters Report
76	15.5	A
76F	7.3	D
PC Amb Low	12.0	ABC
PC Amb High	8.7	CD
PC Cryo Low	11.2	ABCD
PC Cryo High	10.0	BCD
TT Amb Low	12.3	ABC
TT Amb High	10.8	BCD
TT Cryo Low	11.2	ABCD
TT Cryo High	14.1	AB

Table 4.12 shows how the unaged abrasion loss was not influenced by tire type. Table 4.13 shows that the processing method overall did not affected the outcome, as well as it can be seen for blending method in Table 4.14. TT mixes were comparable to 76 in unaged abrasion resistance and PC mixes were similar to 76F. Cryo rubber yielded similar results to 76F and Amb rubber was similar to 76. Low shear influenced the performance similar to the 76 mix and high shear was comparable to 76F.

Table 4.12 - Effect of Tire Type on Abrasion Resistance in Unaged Specimens

Mix	Connecting Letters Report
76	A
76F	C
PC	BC
TT	AB

Table 4.13 - Effect of Processing Method on Abrasion Resistance in Unaged Specimens

Mix	Connecting Letters Report
76	A
76F	C
Amb	AB
Cryo	BC

Table 4.14 - Effect of Blending Method on Abrasion Resistance in Unaged Specimens

Mix	Connecting Letters Report
76	A
76F	C
Low	A
High	BC

Table 4.15 shows the aged average abrasion loss and results of the statistical analysis. The control 76 mix was similar to PC Amb Low, TT Amb Low, TT Cryo Low and TT Cryo High. 76F was similar to all the mixes except 76, PC Amb Low, TT Amb Low, TT Cryo Low and TT Cryo High. Tables 4.16, 4.17, and 4.18 reveal that no research variable had an effect on the aged abrasion loss with the rubber modified asphalt. These tables also show that there was a statistical difference between both the 76 and 76F as well as the experimental mixes. Although the aged specimens were not affected by the variables in the same manner, the unaged specimens were. Table 4.19 shows that there was no significant difference between the unaged and aged abrasion loss results.

Table 4.15 - Statistical Analysis of Abrasion Resistance in Aged Specimens

Mix	Average Aged Abrasion Loss (%)	Connecting Letters Report
76	18.0	A
76F	8.5	D
PC Amb Low	14.5	ABC
PC Amb High	10.3	CD
PC Cryo Low	12.3	BCD
PC Cryo High	11.3	BCD
TT Amb Low	13.6	ABC
TT Amb High	12.5	BCD
TT Cryo Low	15.2	AB
TT Cryo High	15.0	AB

Table 4.16 - Effect of Tire Type on Abrasion Resistance in Aged Specimens

Mix	Connecting Letters Report
76	A
76F	C
PC	BC
TT	B

Table 4.17 - Effect of Processing Method on Abrasion Resistance in Aged Specimens

Mix	Connecting Letters Report
76	A
76F	C
Amb	B
Cryo	B

Table 4.18 - Effect of Blending Method on Abrasion Resistance in Aged Specimens

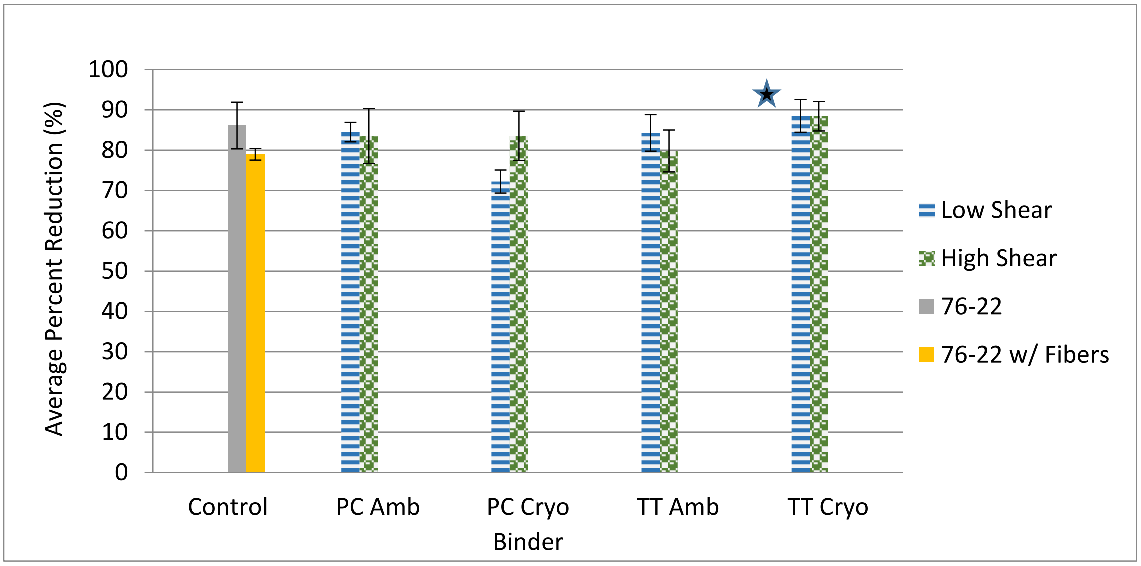
Mix	Connecting Letters Report
76	A
76F	C
Low	B
High	B

Table 4.19 - Statistical Difference of Abrasion Resistance of Mix Between Unaged Specimens and Aged Specimens

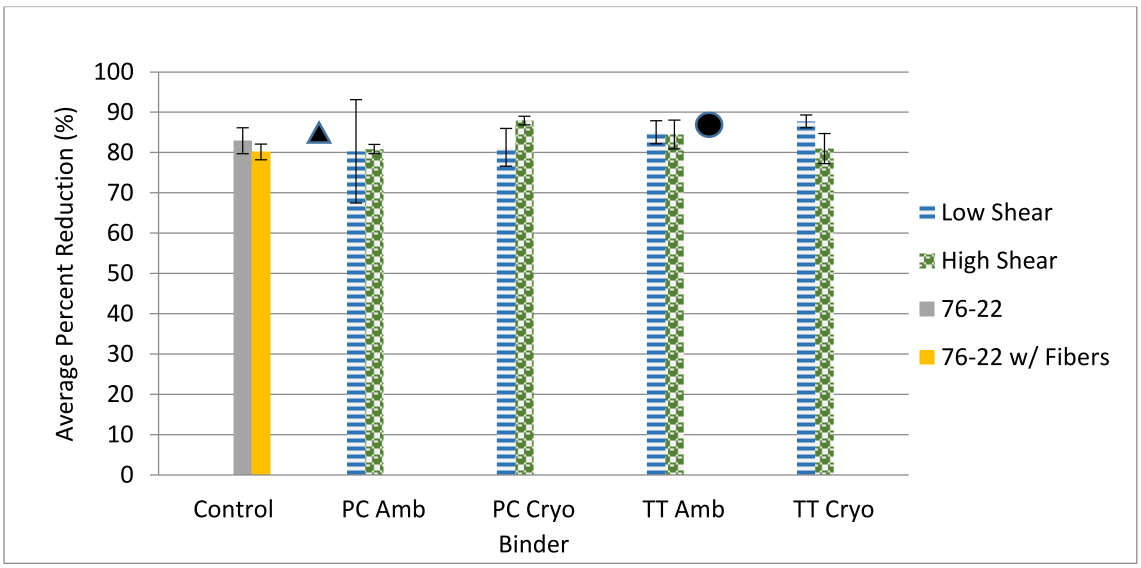
Mix	Significant Difference
76	No
76F	No
PC Amb Low	No
PC Amb High	No
PC Cryo Low	No
PC Cryo High	No
TT Amb Low	No
TT Amb High	No
TT Cryo Low	No
TT Cryo High	No

Fatigue Resistance

Asphalt pavement performance is greatly influenced by outside variables and traffic loadings. Heavy and repeated loadings on an aging pavement can cause permanent deformation and cracking, especially in higher air void asphalt mixtures such as porous asphalt. Fatigue cracking and permanent deformation is considered as the most serious distresses associated with flexible pavements (Hamed 2010). Fatigue, which is the process of cumulative damage resulting from repeated loading, can reduce the service life of the pavement and increase maintenance costs. To compare how resistance can change over time, testing was performed on unaged and aged specimens using the Texas Overlay Test outlined in Chapter 3. The specification of TX-248-F defines failure as a 93% reduction in load from the initial value. The test was stopped at 1200 cycles, if the specimen did not fail. It was assumed that the mixes would perform well due to the high binder content. Figure 4.17 shows the results of the unaged and aged average percent reduction of each mix. Figure 4.17(a) has a star next to the TT Cryo Low shear average percent reduction to show that one test was not completed due to mechanical failure. Figure 4.17(b) displays a triangle and a circle to denote that one PC Amb Low specimen and one TT Amb High specimen failed at 93% prior to 1200 cycles. In the unaged state, the PC Cryo Low mix performed the best with only a 72% load reduction after 1200 cycles. The aged data showed that all the mixes performed relatively the same. Figures 4.18 through 4.22 show the percent reduction curves of each specimen. Out of 30 unaged and 30 aged specimens, only three did not complete 1200 cycles

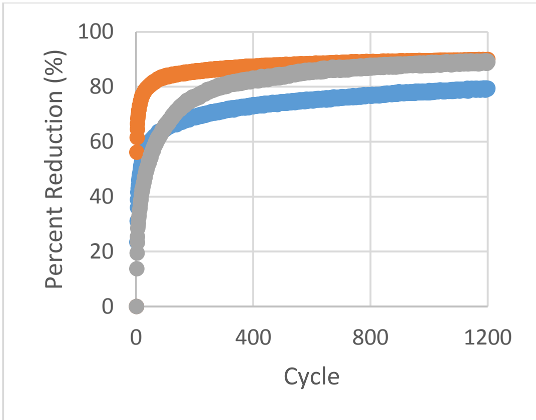


(a)

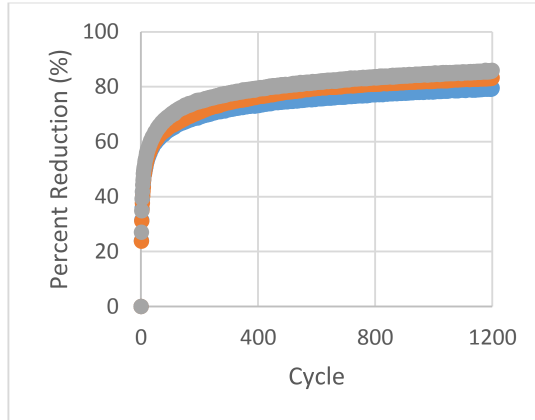


(b)

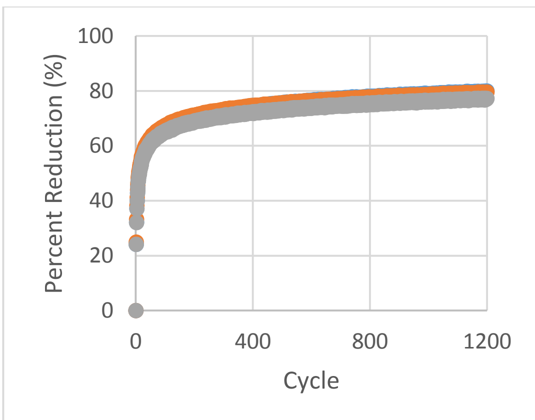
Figure 4.17 - Average Percent Reduction in Fatigue Resistance for Each Mix (a)Unaged Specimens (b) Aged Specimens



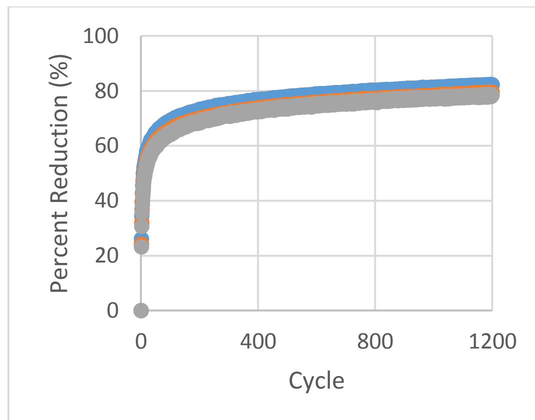
(a)



(b)

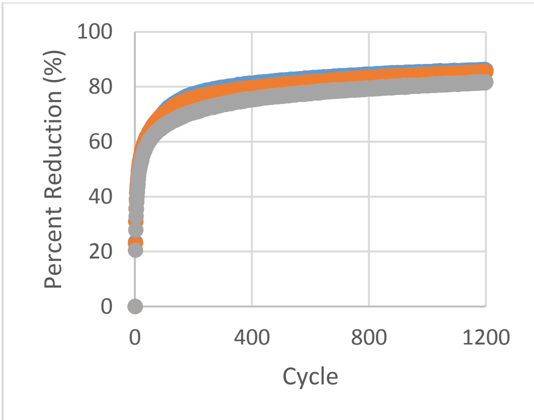


(c)

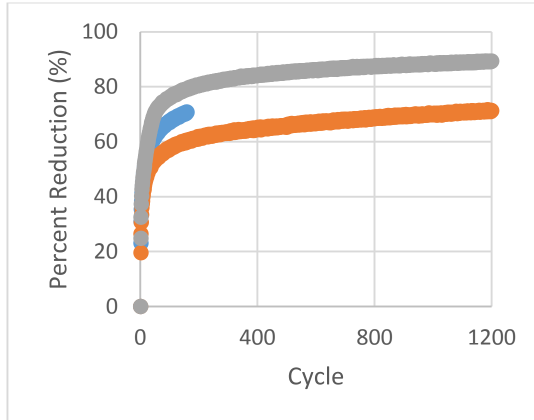


(d)

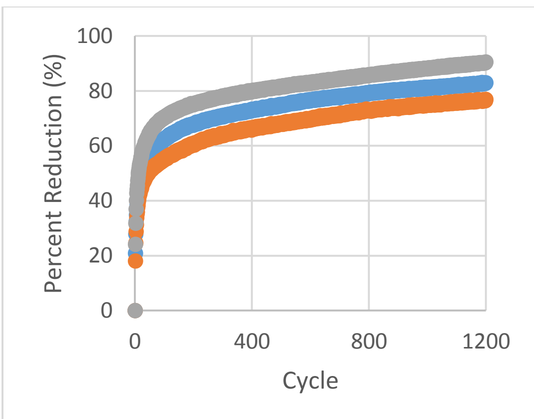
Figure 4.18 - Reduction in Fatigue Resistance of Control Mix
(a) 76 Unaged Specimens (b) 76 Aged Specimens (c) 76F Unaged Specimens (d) 76F Aged Specimens



(a)



(b)



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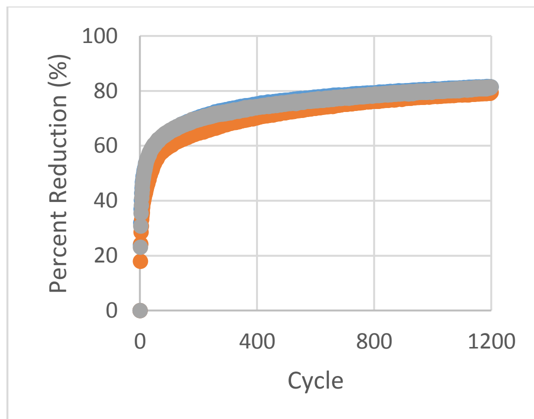


(d)

Figure 4.19 - Reduction in Fatigue Resistance of PC Ambient Mix
(a) Low Unaged Specimens (b) Low Aged Specimens

(c) High Unaged Specimens (d) High Aged Specimens

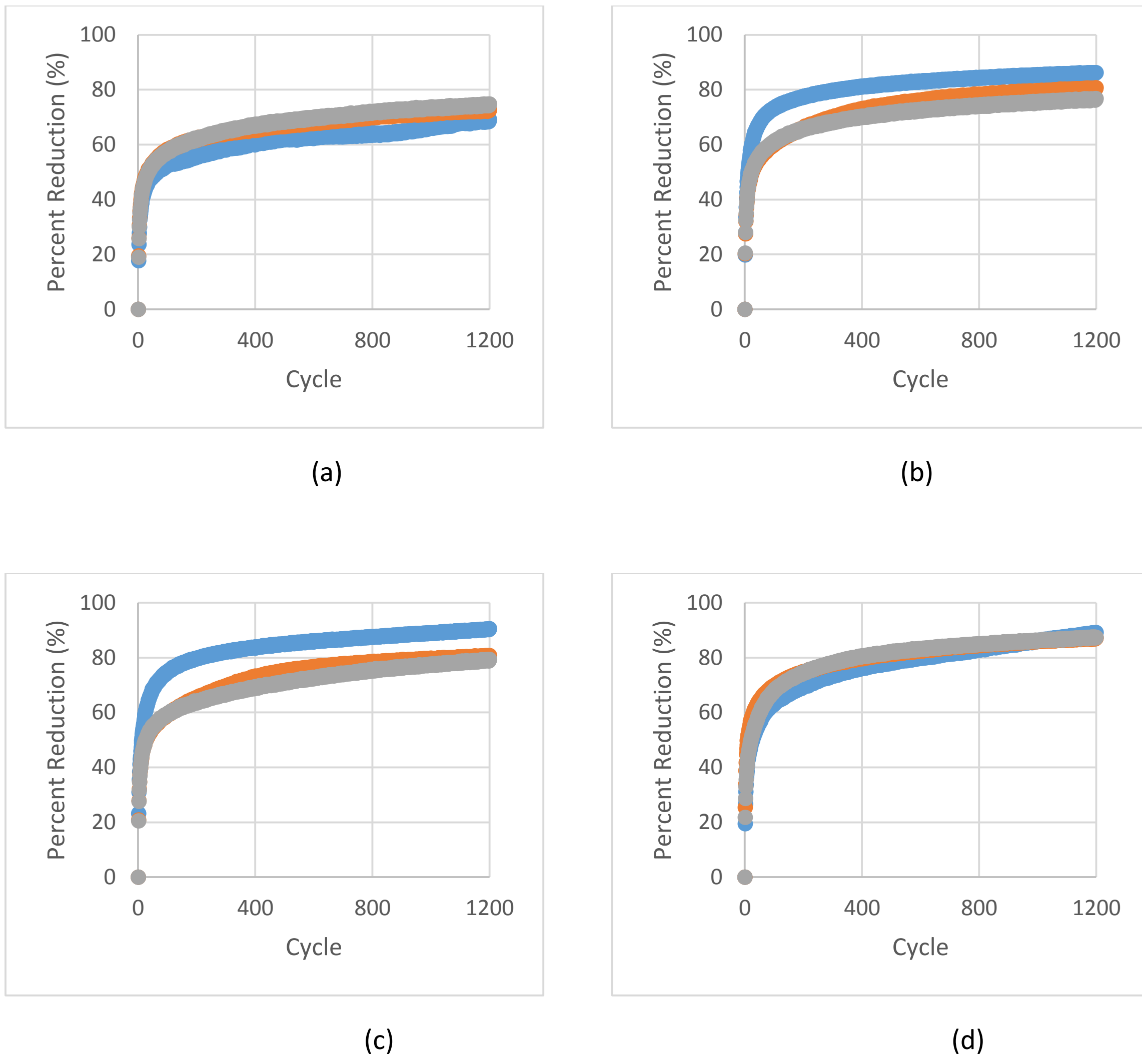
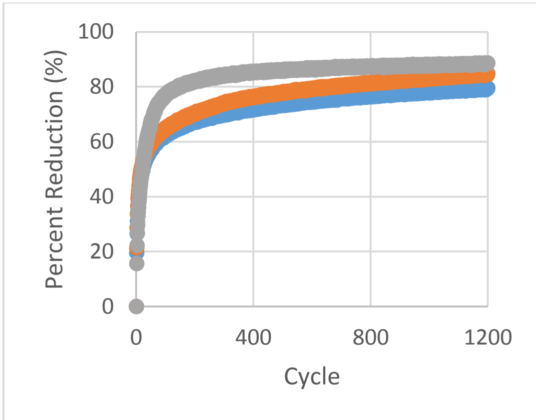
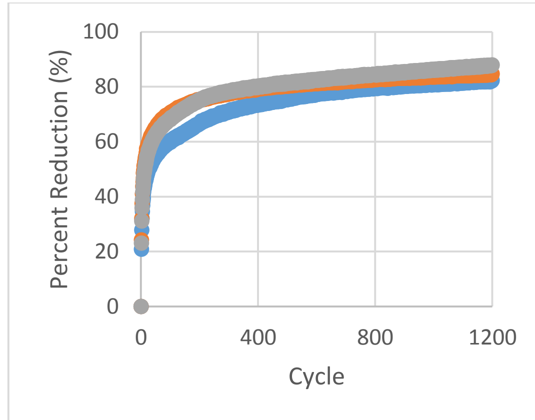


Figure 4.20 - Reduction in Fatigue Resistance of PC Cryogenic Mix
(a) Low Unaged Specimens (b) Low Aged Specimens

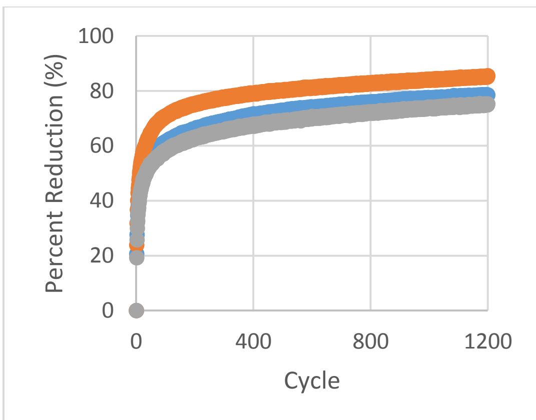
(c) High Unaged Specimens (d) High Aged Specimens



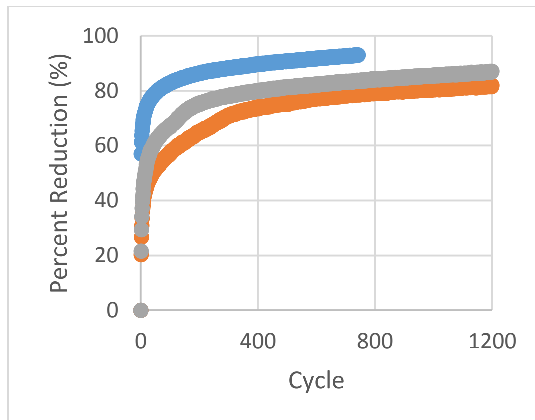
(a)



(b)



(c)



(d)

Figure 4.21 - Reduction in Fatigue Resistance of TT Ambient Mix
(a) Low Unaged Specimens (b) Low Aged Specimens

(c) High Unaged Specimens (d) High Aged Specimens

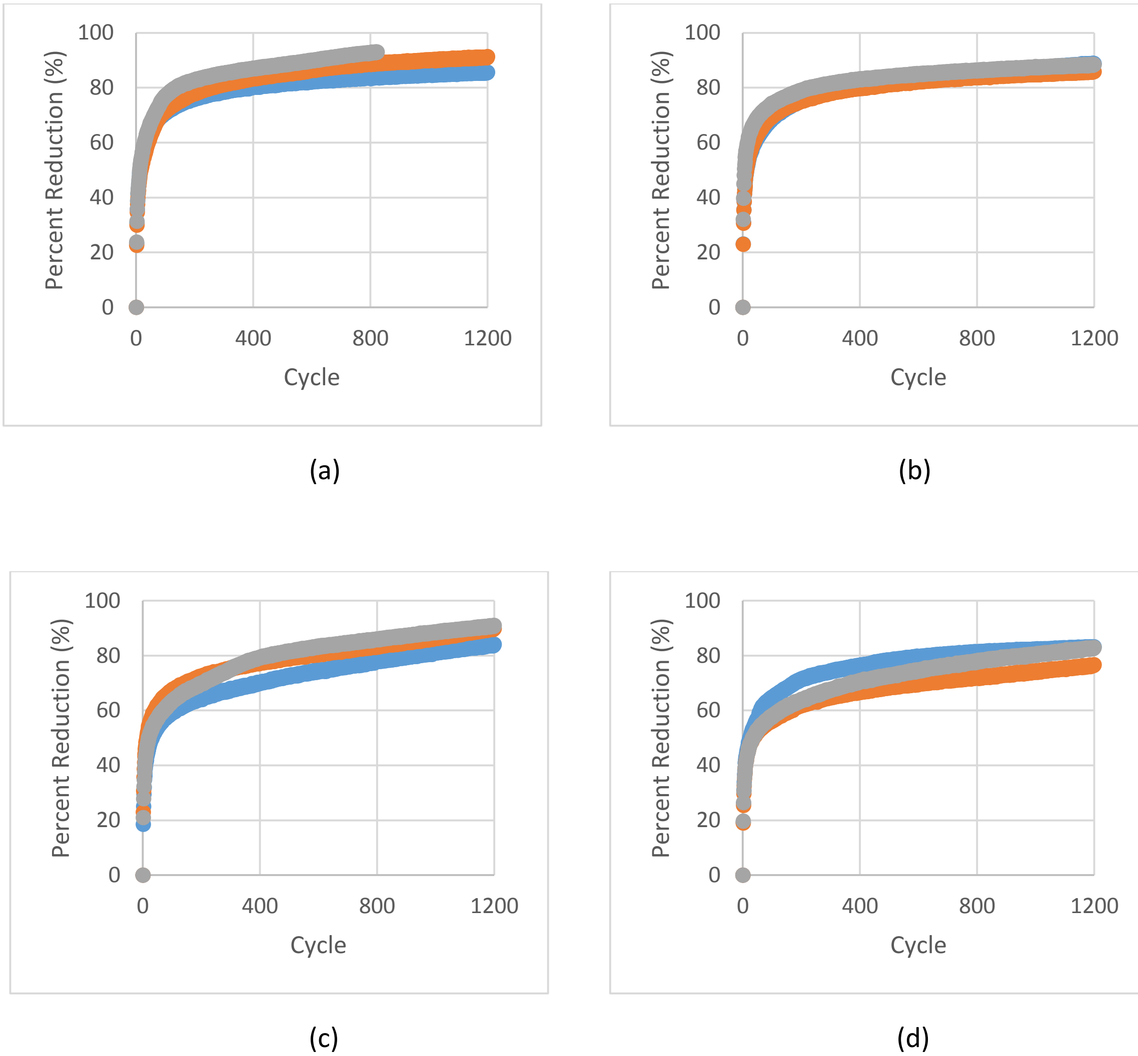
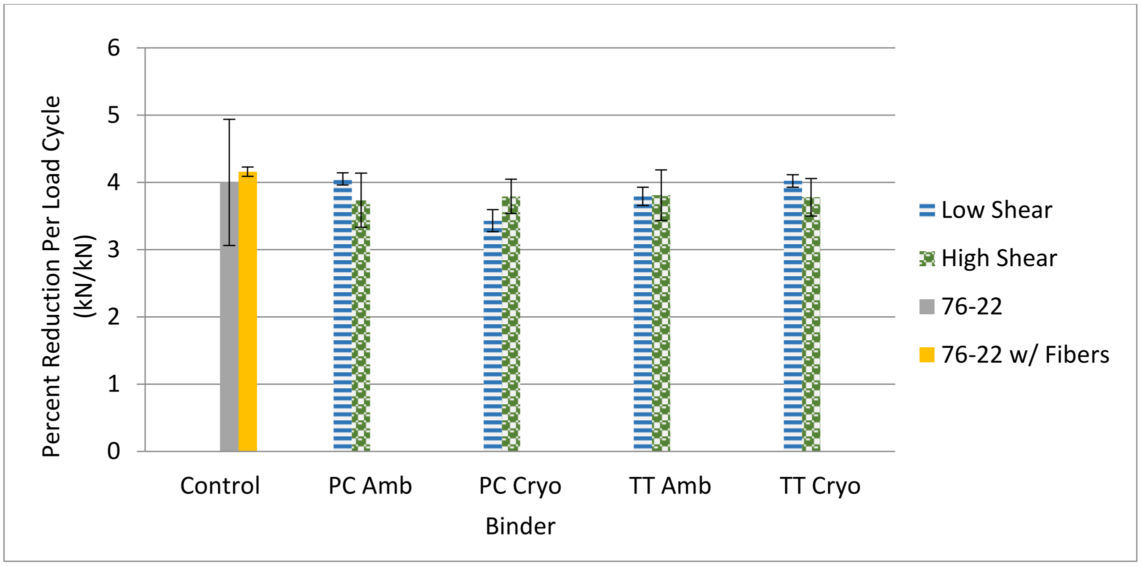


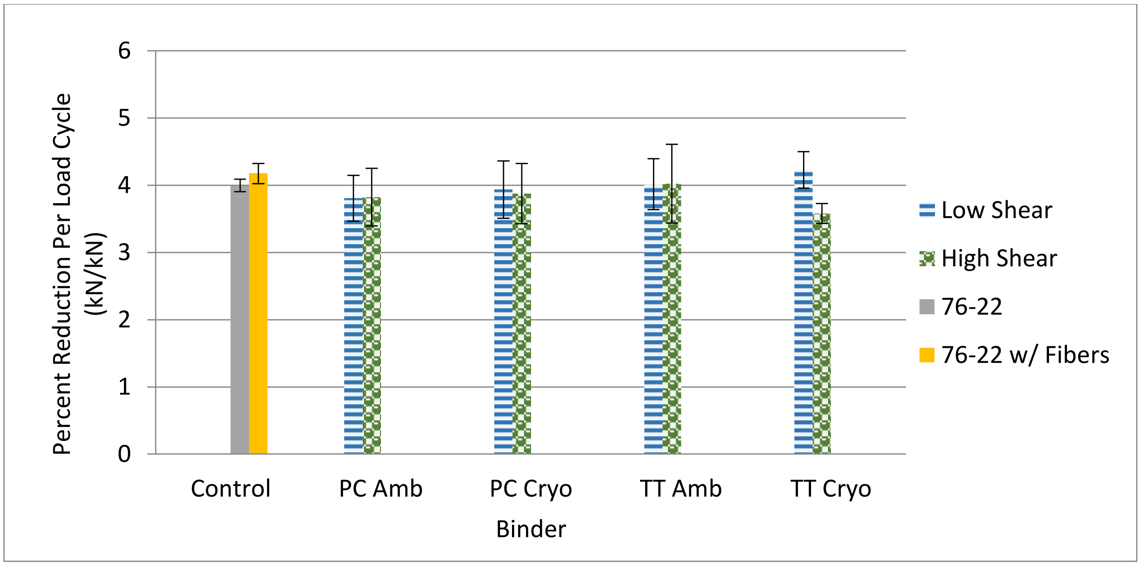
Figure 4.22 - Reduction in Fatigue Resistance of TT Cryogenic Mix
(a) Low Unaged Specimens (b) Low Aged Specimens

(c) High Unaged Specimens (d) High Aged Specimens

To investigate the response to the initial loading and the delayed response throughout the test, the slopes of the reduction curves were analyzed. Figure 4.23 shows the slopes for both unaged and aged specimens from 0-10 cycles. The unaged data shows that the specimens responded in a similar fashion except for PC Cryo Low with had a low initial slope. The aged data showed very similar results. The aged TT Cryo High average had the lowest slope of all the mixes. Figure 4.24 shows the slopes for unaged and aged slopes from 400-1200 cycles. The unaged data shows that the PC Amb High and the TT Cryo High average slopes were significantly higher than the other mixes. The aged data showed the PC Cryo High and the TT Cryo High had higher slopes. This may have been due to the fact that the high shear blending tore the particles into smaller pieces and may have affected the strength of the bond of the rubber particle and the binder.

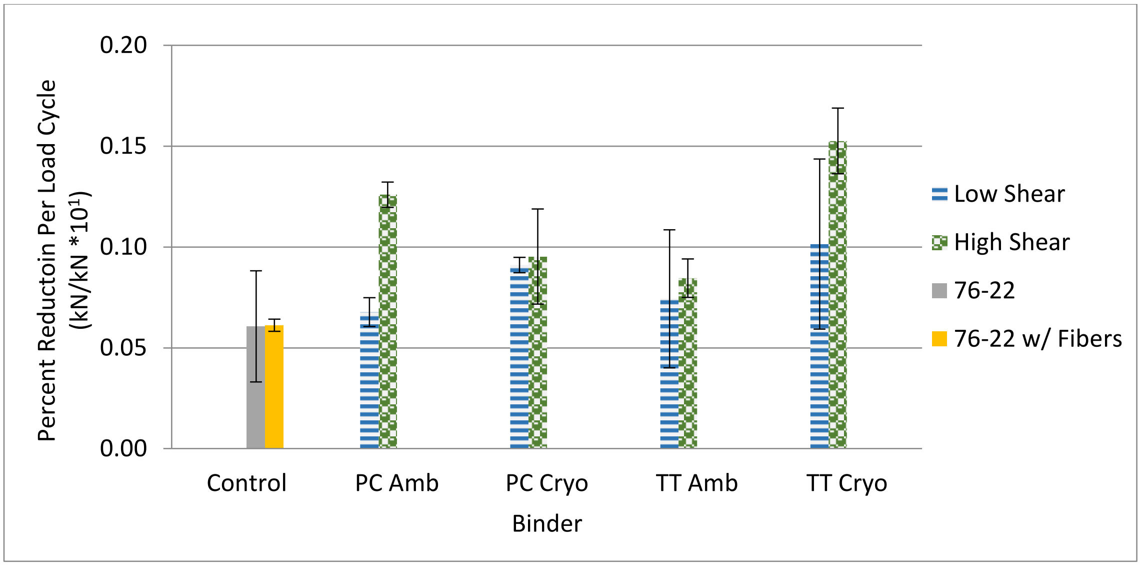


(a)

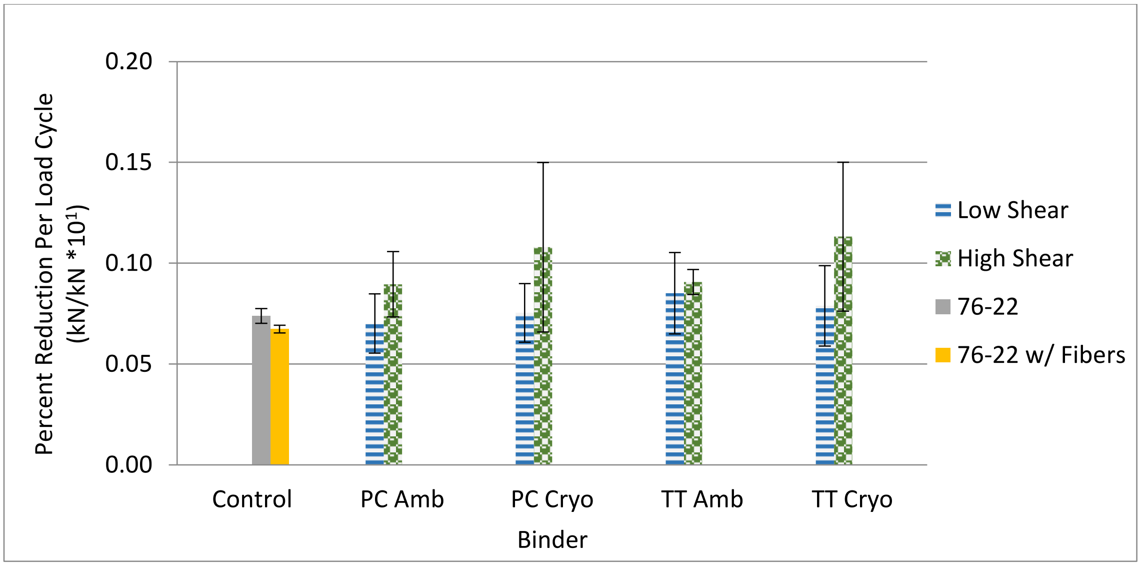


(b)

Figure 4.23 - Average Slope of Percent Reduction in Fatigue Resistance at 0-10 Cycles for Each Mix
(a)Unaged Specimens (b) Aged Specimens



(a)



(b)

Figure 4.24 - Average Slope of Percent Reduction in Fatigue Resistance at 400-1200 Cycles for Each Mix
(a)Unaged Specimens (b) Aged Specimens

The statistical analysis along with the average load reduction of the unaged specimens in Table 4.20 show that 76, PC Amb Low, PC Amb High, PC Cryo High, TT Amb Low, TT Cryo Low and TT Cryo High were statistically similar. 76F, PC Cryo Low and TT Amb High are similar to each other. Tables 4.21, 4.22, and 4.23 show that no research variable affected the unaged fatigue resistance of the mixes and all mixes were statistically similar to each other. .

Table 4.20 - Statistical Analysis of Fatigue Resistance in Unaged Specimens

Mix	Average Unaged Load Reduction (%)	Connecting Letters Report
76	86.1	AB
76F	79.0	BC
PC Amb Low	84.5	AB
PC Amb High	83.5	AB
PC Cryo Low	72.2	C
PC Cryo High	83.6	AB
TT Amb Low	84.3	AB
TT Amb High	79.8	BC
TT Cryo Low	88.5	A
TT Cryo High	88.4	A

Table 4.21 - Effect of Tire Type on Fatigue Resistance in Unaged Specimens

Mix	Connecting Letters Report
76	A
76F	A
PC	A
TT	A

Table 4.22 - Effect of Processing Method on Fatigue Resistance in Unaged Specimens

Mix	Connecting Letters Report
76	A
76F	A
Amb	A
Cryo	A

Table 4.23 – Effect of Blending Method on Fatigue Resistance in Unaged Specimens

Mix	Connecting Letters Report
76	A
76F	A
Low	A
High	A

In Table 4.24, it shows the average load reduction and statistical analysis of aged mixes. The control mixes are similar as well as the TT mixes. The PC Amb Low, PC Amb High and PC Cryo Low mixes are not statistically different. Tables 4.25 through 4.27 show that no effect of the variables were seen on the aged fatigue resistance results. There was also no significant difference between unaged and aged fatigue resistance shown in Table 4.28.

Table 4.24 - Statistical Analysis of Fatigue Resistance in Aged Specimens

Mix	Average Aged Load Reduction (%)	Connecting Letters Report
76	83.0	ABC
76F	80.2	BC
PC Amb Low	80.3	C
PC Amb High	80.9	ABC
PC Cryo Low	81.3	ABC
PC Cryo High	87.9	A
TT Amb Low	85.0	AB
TT Amb High	84.5	AB
TT Cryo Low	87.7	AB
TT Cryo High	81.0	ABC

Table 4.25 - Effect of Tire Type on Fatigue Resistance in Aged Specimens

Mix	Connecting Letters Report
76	A
76F	A
PC	A
TT	A

Table 4.26 - Effect of Processing Method on Fatigue Resistance in Aged Specimens

Mix	Connecting Letters Report
76	A
76F	A
Amb	A
Cryo	A

Table 4.27 - Effect of Blending Method on Fatigue Resistance in Aged Specimens

Mix	Connecting Letters Report
76	A
76F	A
Low	A
High	A

Table 4.28 - Statistical Difference of Fatigue Resistance of Mix Between Unaged Specimens and Aged Specimens

Mix	Significant Difference
76	No
76F	No
PC Amb Low	No
PC Amb High	No
PC Cryo Low	No
PC Cryo High	No
TT Amb Low	No
TT Amb High	No
TT Cryo Low	No
TT Cryo High	No

Dynamic Modulus

In flexible pavements, rutting is considered as one of the most detrimental effects on safety. Rutting is caused by the continuous repeated loadings of traffic in the wheel paths. The load from heavy vehicles and smaller vehicles causes the pavement to compact as time progresses. This causes air voids to decrease in a porous asphalt mixture and can cause the reduction of water flow. In previous research, dynamic modulus (E*) has been correlated with rutting susceptibility (Apeagyei 2011). When comparing E*, a result of 8000 MPa is less likely to deform in terms of rutting compared to a result of 6000 MPa. This research utilized an AMPT to test the 10 mixes at 3 temperatures of 4°C, 20°C and 45°C. The test was completed following the procedure discussed in Chapter 3.

The statistical analysis in Table 4.29 displays the results of the tests completed at 4°C. At a frequency of 10 Hz 76, 76F and PC Amb Low were similar, the PC Cryo mixes and PC Amb High were similar and the TT Cryo mixes and TT Amb High were similar. TT Amb Low was only similar to the PC Amb High, PC Cryo Low and the TT Amb High mixes. In Tables 4.30, 4.31 and 4.32, it is shown that the research variables did not create different results within the rubber modified mixes. However, there was a statistical difference between the control and rubber modified mixes.

Table 4.29 - Statistical Analysis of Dynamic Modulus Tested at 4°C (10 Hz)

Mix	Average Dynamic Modulus (MPa)	Connecting Letters Report
76	8212	AB
76F	8575	A
PC Amb Low	7674	ABC
PC Amb High	6740	CD
PC Cryo Low	6811	CD
PC Cryo High	7591	BC
TT Amb Low	6220	D
TT Amb High	7083	CD
TT Cryo Low	7365	BC
TT Cryo High	7360	BC

Table 4.30 - Effect of Tire Type on of Dynamic Modulus Tested at 4°C (10 Hz)

Mix	Connecting Letters Report
76	A
76F	A
PC	B
TT	B

Table 4.31 - Effect of Processing Method on of Dynamic Modulus Tested at 4°C (10 Hz)

Mix	Connecting Letters Report
76	A
76F	A
Amb	B
Cryo	B

Table 4.32 - Effect of Blending Method on of Dynamic Modulus Tested at 4°C (10 Hz)

Mix	Connecting Letters Report
76	A
76F	A
Low	B
High	B

At 1 Hz, there was a similar trend as the 10 Hz frequency shown in Table 4.33, however, there with more similarities throughout the different mixes. Table 4.34 shows that the tire type yielded similar results within the rubber modified asphalt but were not comparable to the control mixes. The processing method did have a significant effect on the dynamic modulus when considering the rubber modified mixtures. However, the Cryo mixes were similar to the 76 mix as seen in Table 4.35. Table 4.36 shows that the low and high shear mixes were similar to each other but were not comparable to the control mixes. All rubber modified mixes were comparable to each other while 76F was only comparable to 76.

Table 4.33 - Statistical Analysis of Dynamic Modulus Tested at 4°C (1 Hz)

Mix	Average Dynamic Modulus (MPa)	Connecting Letters Report
76	6056	AB
76F	6289	A
PC Amb Low	5663	ABC
PC Amb High	4877	DE
PC Cryo Low	5090	CDE
PC Cryo High	5616	ABCD
TT Amb Low	4464	E
TT Amb High	5198	CDE
TT Cryo Low	5566	ABCD
TT Cryo High	5473	BCD

Table 4.34 - Effect of Tire Type on Dynamic Modulus Tested at 4°C (1 Hz)

Mix	Connecting Letters Report
76	A
76F	A
PC	B
TT	B

Table 4.35 - Effect of Processing Method on Dynamic Modulus Tested at 4°C (1 Hz)

Mix	Connecting Letters Report
76	AB
76F	A
Amb	C
Cryo	BC

Table 4.36 - Effect of Blending Method on Dynamic Modulus Tested at 4°C (1 Hz)

Mix	Connecting Letters Report
76	A
76F	A
Low	B
High	B

Table 4.37 shows the last frequency tested at 4°C. This frequency resulted in a similar report as the 1 Hz frequency did. Tables 4.38, 4.39, and 4.40 show that within the experimental mixes, tire type and blending method resulted in similar values to 76 but the processing method of Amb did not result in similar dynamic modulus values as any other mix. The experimental mixes were only similar to 76 in terms of tire type. Amb rubber resulted in similarities to only Amb mixes, Cryo rubber yielded similarities to only the two control mixes and the blending methods gave comparable values to 76.

Table 4.37 - Statistical Analysis of Dynamic Modulus Tested at 4°C (0.1 Hz)

Mix	Average Dynamic Modulus (MPa)	Connecting Letters Report
76	4089	AB
76F	4217	A
PC Amb Low	3847	AB
PC Amb High	3230	CD
PC Cryo Low	3500	BCD
PC Cryo High	3815	ABC
TT Amb Low	2957	D
TT Amb High	3528	BCD
TT Cryo Low	3895	AB
TT Cryo High	3766	ABC

Table 4.38 - Effect of Tire Type on Dynamic Modulus Tested at 4°C (0.1 Hz)

Mix	Connecting Letters Report
76	AB
76F	A
PC	B
TT	B

Table 4.39 - Effect of Processing Method on Dynamic Modulus Tested at 4°C (0.1 Hz)

Mix	Connecting Letters Report
76	A
76F	A
Amb	B
Cryo	A

Table 4.40 - Effect of Blending Method on Dynamic Modulus Tested at 4°C (0.1 Hz)

Mix	Connecting Letters Report
76	AB
76F	A
Low	B
High	B

The statistical analysis results in Tables 4.41, 4.42, 4.43 and 4.44 display the results of the tests completed at 20°C. At a frequency of 10 Hz in Table 4.41, mixes 76, 76F and PC Amb Low were similar, the PC Cryo mixes and PC Amb High were similar and the TT Cryo mixes were similar to only each other and TT Amb mixes were as well. TT Amb Low was only similar to the PC Amb High, PC Cryo Low and the TT Amb High mixes. In Tables 4.42, 4.43, and 4.44 it is shown that the research variables of tire type and blending method did not affect the results, however, there was a statistical difference between the mixes in regards to processing method. As seen in Table 4.43, only the Cryo rubber was similar to the control mixes, while the Amb mixes were comparable to the Cryo rubber mixes.

Table 4.41 - Statistical Analysis of Dynamic Modulus Tested at 20°C (10 Hz)

Mix	Average Dynamic Modulus (MPa)	Connecting Letters Report
76	3995	A
76F	3976	AB
PC Amb Low	3838	AB
PC Amb High	3256	CD
PC Cryo Low	3451	BCD
PC Cryo High	3734	ABC
TT Amb Low	3102	D
TT Amb High	3552	ABCD
TT Cryo Low	3819	AB
TT Cryo High	3685	ABC

Table 4.42 - Effect of Tire Type on Dynamic Modulus Tested at 20°C (10 Hz)

Mix	Connecting Letters Report
76	A
76F	A
PC	A
TT	A

Table 4.43 - Effect of Processing Method on Dynamic Modulus Tested at 20°C (10 Hz)

Mix	Connecting Letters Report
76	A
76F	A
Amb	B
Cryo	AB

Table 4.44 - Effect of Blending Method on Dynamic Modulus Tested at 4°C (0.1 Hz)

Mix	Connecting Letters Report
76	A
76F	A
Low	A
High	A

At 1 Hz, there was a more consistent trend than the 10 Hz frequency shown in Table 4.45. 76 was similar to 76F, PC Amb Low, PC Cryo mixes, TT Amb High and the TT Cryo mixes. Tables 4.46, 4.47 and 4.48 show that neither the tire type, processing method nor blending method affected the results and yielded similar performance in all mixes.

Table 4.45 - Statistical Analysis of Dynamic Modulus Tested at 20°C (1 Hz)

Mix	Average Dynamic Modulus (MPa)	Connecting Letters Report
76	2303	A
76F	2262	A
PC Amb Low	2248	A
PC Amb High	1822	BC
PC Cryo Low	2020	ABC
PC Cryo High	2184	AB
TT Amb Low	1729	C
TT Amb High	2096	ABC
TT Cryo Low	2282	A
TT Cryo High	2167	AB

Table 4.46 - Effect of Tire Type on Dynamic Modulus Tested at 20°C (1 Hz)

Mix	Connecting Letters Report
76	A
76F	A
PC	A
TT	A

Table 4.47 - Effect of Processing Method on Dynamic Modulus Tested at 20°C (1 Hz)

Mix	Connecting Letters Report
76	A
76F	AB
Amb	B
Cryo	AB

Table 4.48 - Effect of Blending Method on Dynamic Modulus Tested at 20°C (1 Hz)

Mix	Connecting Letters Report
76	A
76F	A
Low	A
High	A

Table 4.49 shows the last frequency of 0.01 Hz tested at 20°C. This frequency resulted in a very high similarity report. 76, 76F, PC Amb Low, PC Cryo mixes, TT Amb High and TT Cryo High were all similar to each other. PC Amb High was similar to the PC Cryo and TT Amb mixes. Tables 4.50, 4.51, and 4.52 show that none of the variables caused a significant difference from the control mixes.

Table 4.49 - Statistical Analysis of Dynamic Modulus Tested at 20°C (0.1 Hz)

Mix	Average Dynamic Modulus (MPa)	Connecting Letters Report
76	1194	A
76F	1153	A
PC Amb Low	1176	A
PC Amb High	904	B
PC Cryo Low	1052	AB
PC Cryo High	1130	AB
TT Amb Low	899	B
TT Amb High	1106	AB
TT Cryo Low	1211	A
TT Cryo High	1148	A

Table 4.50 - Effect of Tire Type on Dynamic Modulus Tested at 20°C (0.1 Hz)

Mix	Connecting Letters Report
76	A
76F	A
PC	A
TT	A

Table 4.51 - Effect of Processing Method on Dynamic Modulus Tested at 20°C (0.1 Hz)

Mix	Connecting Letters Report
76	A
76F	A
Amb	A
Cryo	A

Table 4.52 - Effect of Blending Method on Dynamic Modulus Tested at 20°C (0.1 Hz)

Mix	Connecting Letters Report
76	A
76F	A
Low	A
High	A

The statistical analysis presented in Tables 4.53, 4.54, 4.55 and 4.56 display the results of the tests completed at 45°C with a frequency of 10 Hz. Shown in Table 4.53, 76, 76F, PC Amb Low, PC Cryo High, TT Amb High and the TT Cryo mixes were similar. PC Amb High, PC Cryo Low and TT Amb Low were all similar to each other. Table 4.54 and 4.56 shows that the research variables of tire type and blending method did not result in a statistical difference within the rubber modified mixes, however the rubber modified asphalt mixes were only comparable to 76F shown in Table 4.54.

Table 4.53 - Statistical Analysis of Dynamic Modulus Tested at 45°C (10 Hz)

Mix	Average Dynamic Modulus (MPa)	Connecting Letters Report
76	766	A
76F	654	AB
PC Amb Low	671	AB
PC Amb High	508	B
PC Cryo Low	549	B
PC Cryo High	594	AB
TT Amb Low	586	B
TT Amb High	599	AB
TT Cryo Low	668	AB
TT Cryo High	628	AB

Table 4.54 - Effect of Tire Type on Dynamic Modulus Tested at 45°C (10 Hz)

Mix	Connecting Letters Report
76	A
76F	AB
PC	B
TT	B

Table 4.55 - Effect of Processing Method on Dynamic Modulus Tested at 45°C (10 Hz)

Mix	Connecting Letters Report
76	A
76F	AB
Amb	B
Cryo	B

Table 4.56 - Effect of Blending Method on Dynamic Modulus Tested at 45°C (10 Hz)

Mix	Connecting Letters Report
76	A
76F	AB
Low	B
High	B

At 1 Hz, there was a consistency shown in Table 4.57. Mix 76 was similar to 76F, PC Amb Low and the TT mixes and all rubber modified mixes were comparable to 76F shown in Table 4.57. Tables 4.58, 4.59, and 4.60 show that none of the variables affected similarity of the experimental mixes but they were only similar to the 76F mix.

Table 4.57 - Statistical Analysis of Dynamic Modulus Tested at 45°C (1 Hz)

Mix	Average Dynamic Modulus (MPa)	Connecting Letters Report
76	288	A
76F	241	AB
PC Amb Low	238	AB
PC Amb High	164	B
PC Cryo Low	184	B
PC Cryo High	198	B
TT Amb Low	212	AB
TT Amb High	209	AB
TT Cryo Low	228	AB
TT Cryo High	218	AB

Table 4.58 - Effect of Tire Type on Dynamic Modulus Tested at 45°C (1 Hz)

Mix	Connecting Letters Report
76	A
76F	AB
PC	B
TT	B

Table 4.59 - Effect of Processing Method on Dynamic Modulus Tested at 45°C (1 Hz)

Mix	Connecting Letters Report
76	A
76F	AB
Amb	B
Cryo	B

Table 4.60 - Effect of Blending Method on Dynamic Modulus Tested at 45°C (1 Hz)

Mix	Connecting Letters Report
76	A
76F	AB
Low	B
High	B

Table 4.61 shows the results of 0.01 Hz at 45°C. This frequency resulted in similarity amongst all the rubber modified asphalt mixes. The only experimental mixes that were not comparable to 76F were PC Amb High and PC Cryo Low. At this frequency, 76 was only similar to 76F. Tables 4.62, 4.63, and 4.64 show that all of the individual variables caused a significant difference from the 76 mix. In terms of tire type, none of the experimental mixes were comparable to 76. The TT mixes were comparable to the 76F mix, while the rubber modified mixes were all similar to each other through the statisticall analysi of all three individual variables. The rubber processing method resulted in similarities of the experimental mixes. The

processing method of Amb rubber was similar to 76F. Blending method affected the similarity of low shear to 76F and high shear was only similar to the low shear mixes.

Table 4.61 - Statistical Analysis of Dynamic Modulus Tested at 45°C (0.1 Hz)

Mix	Average Dynamic Modulus (MPa)	Connecting Letters Report
76	126	A
76F	104	AB
PC Amb Low	89	BC
PC Amb High	57	C
PC Cryo Low	66	C
PC Cryo High	71	BC
TT Amb Low	83	BC
TT Amb High	81	BC
TT Cryo Low	78	BC
TT Cryo High	80	BC

Table 4.62 - Effect of Tire Type on Dynamic Modulus Tested at 45°C (0.1 Hz)

Mix	Connecting Letters Report
76	A
76F	AB
PC	C
TT	BC

Table 4.63 - Effect of Processing Method on Dynamic Modulus Tested at 45°C (0.1 Hz)

Mix	Connecting Letters Report
76	A
76F	AB
Amb	BC
Cryo	C

Table 4.64 - Effect of Blending Method on Dynamic Modulus Tested at 45°C (0.1 Hz)

Mix	Connecting Letters Report
76	A
76F	AB
Low	BC
High	C

Table 4.65 presents the fact that all of the rubber modified mixes were comparable to other rubber mixes but not to the 76 or 76F mixes at 45°C and 0.01 Hz. Tables 4.66, 4.67, and 4.68 show that all the variables resulted in similar values in the experimental mixes and were not comparable to the control mixes. From this, it can be understood that at high temperatures, the rubber modified asphalt cannot perform to the same standards as the control mixes.

Table 4.65 - Statistical Analysis of Dynamic Modulus Tested at 45°C (0.01 Hz)

Mix	Average Dynamic Modulus (MPa)	Connecting Letters Report
76	66	A
76F	57	A
PC Amb Low	34	B
PC Amb High	26	B
PC Cryo Low	26	B
PC Cryo High	25	B
TT Amb Low	36	B
TT Amb High	33	B
TT Cryo Low	30	B
TT Cryo High	32	B

Table 4.66 - Effect of Tire Type on Dynamic Modulus Tested at 45°C (0.01 Hz)

Mix	Connecting Letters Report
76	A
76F	A
PC	B
TT	B

Table 4.67 - Effect of Processing Method on Dynamic Modulus Tested at 45°C (0.01 Hz)

Mix	Connecting Letters Report
76	A
76F	A
Amb	B
Cryo	B

Table 4.68 - Effect of Blending Method on Dynamic Modulus Tested at 45°C (0.01 Hz)

Mix	Connecting Letters Report
76	A
76F	A
Low	B
High	B

CHAPTER 5
SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

Summary

A porous asphalt is an open-graded asphalt mix that allows water to flow through to the subgrade below. This attribute allows for water to quickly migrate away from the surface of the pavement. Advantages of porous asphalt include benefits to the environment and safety of motorists. This research was conducted to evaluate the effects of rubber modified binder on performance properties of different mixes. The research variables of this research were tire type, processing method and blending method. The objectives of this research were: to determine GTR binder formula to obtain the same continuous grade as the control styrene-butadiene-styrene (SBS) modified PG 76-22 binder, determine the optimum binder content and develop draindown curves for each GTR mix for all ten mixes and determine the influence on performance properties of the porous asphalt mixtures including porosity, permeability, long-term draindown, raveling susceptibility, fatigue resistance, and dynamic modulus.

Conclusions

Based on the results of this study the effects of the rubber modified binder in porous asphalt mixtures, the following conclusions were made:

- To attain binder grade performance similar to the true grade of PG 76-22, more PC rubber was required than TT rubber and more Amb processed rubber was required than Cryo rubber.
- After analyzing all the test data statistical analysis on each variable within this research, rubber modified asphalt can be used in porous asphalt and perform to the same standards as mixes with fibers in certain situations. Depending on

what performance measure is the most important for the potential pavement, these results can be used to formulate a porous asphalt that performs or even out-performs fiber modified asphalt.

- The addition of tire type porosity did not achieve similar values of porosity as the control mixes,
- The processing method and blending method were statistically similar to the control mixes in porosity.
- The addition of either tire type and processing method resulted in similar initial permeability values as 76F
- Both blending methods will result in a similar outcome as 76F in initial permability.
- The addition of TT rubber yielded a more stable and predictable aged permeability over time. This indicates that porous asphalt mixtures made with TT rubber may exhibit less long-term draindown over time compared to other binders.
- The addition of tire type did effect abrasion resistance on unaged and aged asphalt
- Aged asphalt had a higher tolerance to abrasion loss when PC rubber was added compared to TT rubber.
- The addition of either tire type, processing method or blending method resulted in a significant difference on fatigue resistance in unaged and aged asphalt.
- Rutting resistance, as exhibited by the dynamic modulus results, increased with the addition of Cryo rubber at 4°C, 20°C and at 45°C Amb rubber blended with Low shear give the most desirable results.

- The tire type resulted in a substantial difference in porosity and initial permeability
- The performance of the initial permeability, unaged abrasion resistance and some temperatures and frequencies of dynamic modulus was affected by the processing method of rubber.
- Overall, the blending method did not affect the performance of the asphalt

Recommendations

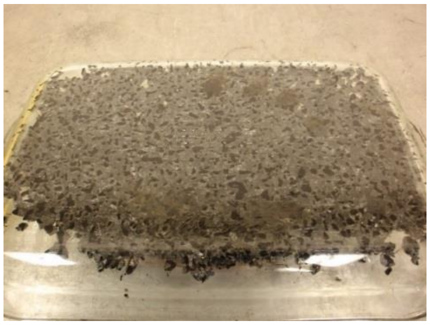
- Investigate the chemical composition of the rubber in terms of tire type and the processing method
- Investigate binder properties through in depth binder testing

After analyzing all the test data statistical analysis on each variable within this research, rubber modified asphalt can be used in porous asphalt and perform to the same standards as mixes with fibers in certain situations. The results of this research rubber can be used to create asphalt mixtures that may help with lowering construction cost and improving the safety of roads. While the experimental mixes did experience a decrease in permeability from long term draindown of the binder, all mixes were an acceptable rate. This could eliminate the issue of hydroplaning as well as creating a system that filters water on its own without the need for stormwater management. Using the dynamic modulus results to infer information about rutting resistance, these rubber modified porous mixes would work better in mild climates than hot climates due to the less desirable results seen in testing at 45°C. The uses of rubber can give benefits through environmental aspects by recycling waste material and creating a permeable surface, help with cost savings by replacing SBS modifier with rubber and increasing road safety by stopping hydroplaning. Depending on what performance measure is the most important for the potential pavement, these results can be used to formulate a porous asphalt that performs or even out-performs fiber modified asphalt.

APPENDICES

APPENDIX A

Optimum Binder Content



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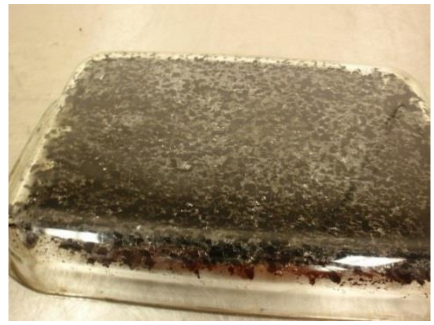

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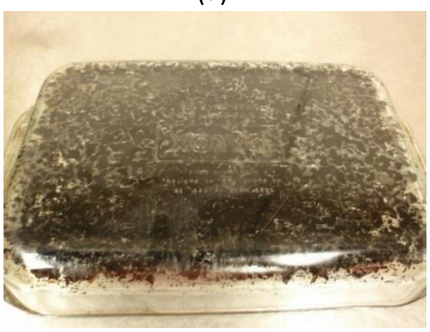

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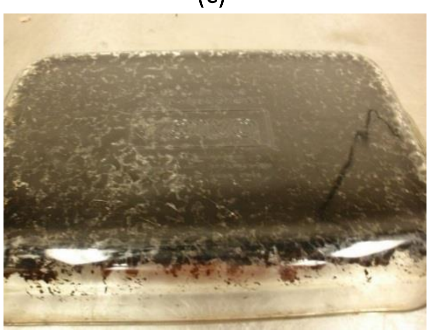

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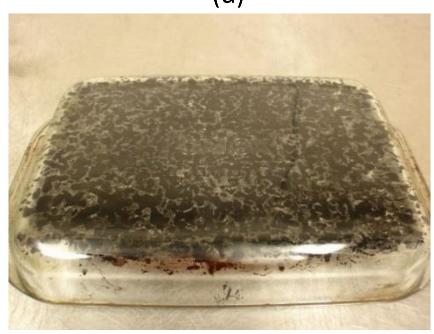
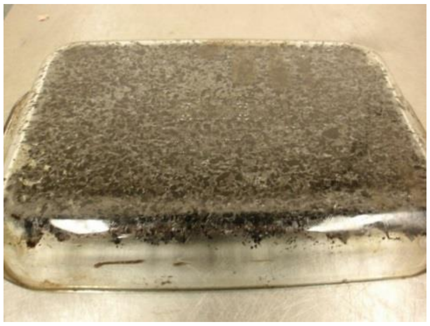


(f)

Figure A.1 - 76-22 Optimum Binder Content
(a) 5.0% - Specimen 1, (b) 5.0% - Specimen 2, (c) 5.5% - Specimen 1, (d) 5.5% - Specimen 2, (e) 6.0% - Specimen 2, (f) 6.0% - Specimen 2



(a)

(b)

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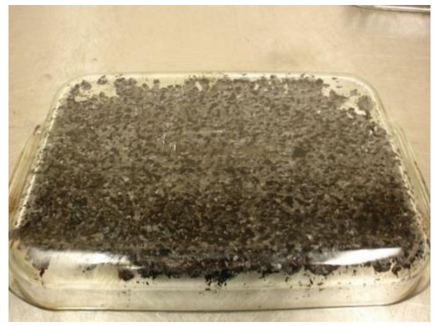

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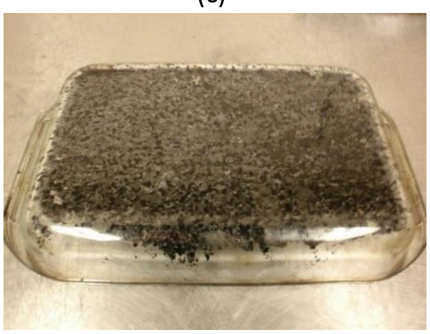

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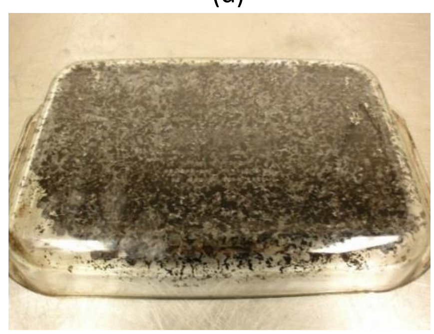
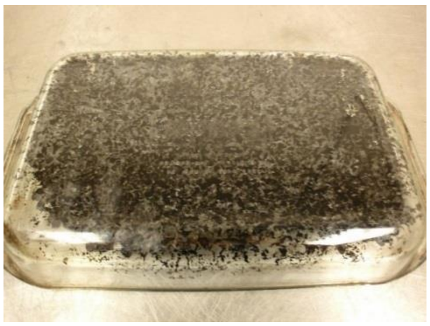


(f)

Figure A.2 - 76-22 With Fibers Optimum Binder Content
(a) 6.0% - Specimen 1, (b) 6.0% - Specimen 2, (c) 6.5% - Specimen 1, (d) 6.5% - Specimen 2, (e) 7.0% - Specimen 2, (f) 7.0% - Specimen 2

(a)

(b)



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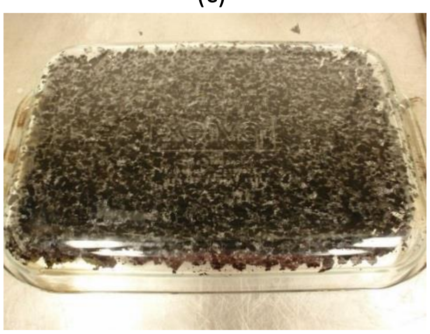

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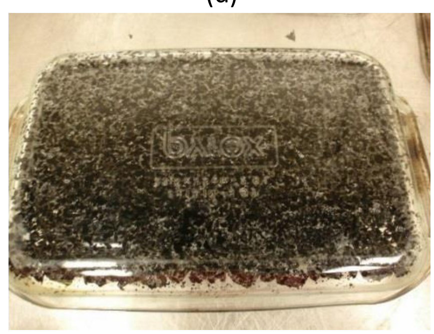

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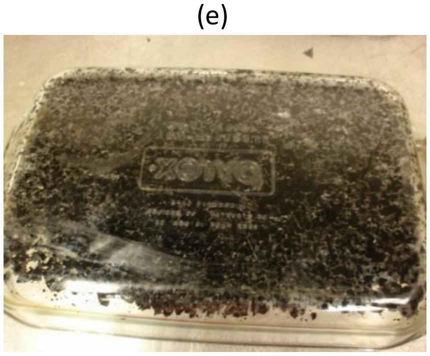

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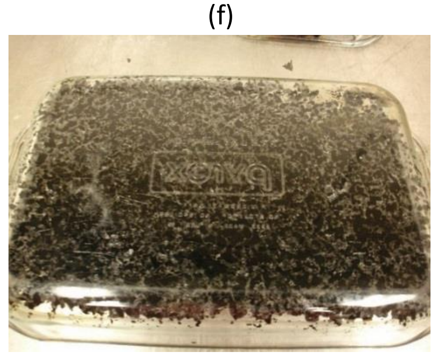
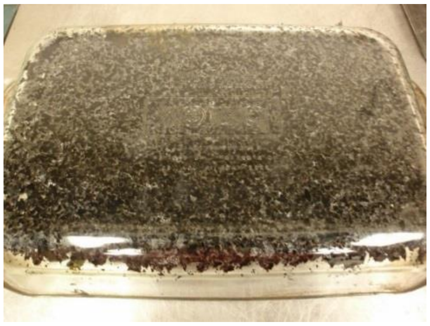


(h)

Figure A. 3 - 16.5% Passenger Car Cryogenic Rubber Low Shear Optimum Binder Content (a) 6.0% - Specimen 1, (b) 6.0% - Specimen 2, (c) 6.5% - Specimen 1, (d) 6.5% - Specimen 2, (e) 7.0% - Specimen 2, (f) 7.0% - Specimen 2, (g) 7.5% - Specimen 1, (h) 7.5% - Specimen 2



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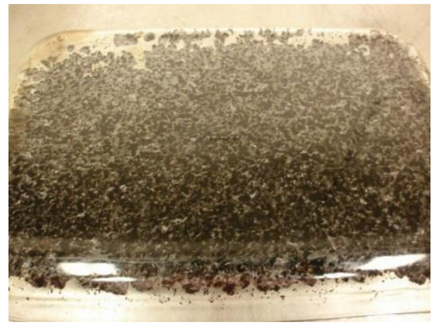

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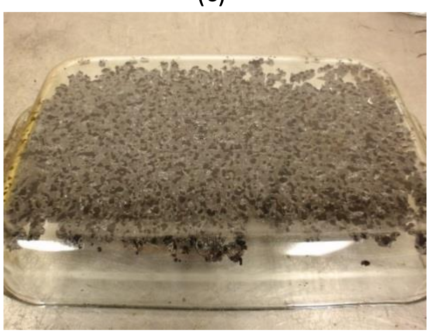

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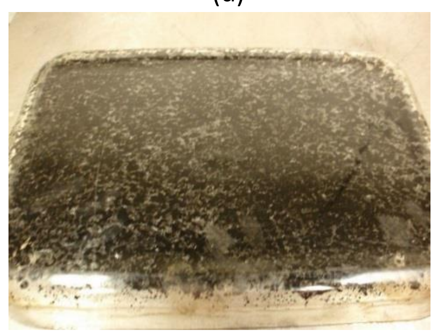

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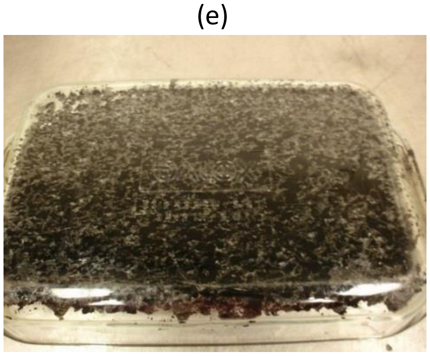

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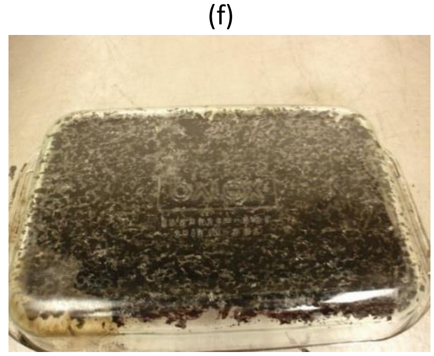

(h)

Figure A.4 - 19.5% Passenger Car Ambient Rubber Low Shear Optimum Binder Content (a) 6.0% - Specimen 1, (b) 6.0% - Specimen 2, (c) 6.5% - Specimen 1, (d) 6.5% - Specimen 2, (e) 7.0% - Specimen 2, (f) 7.0% - Specimen 2, (g) 7.5% - Specimen 1, (h) 7.5% - Specimen 2

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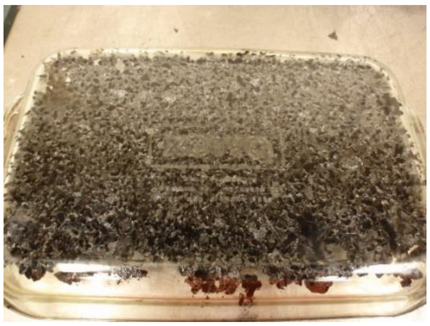

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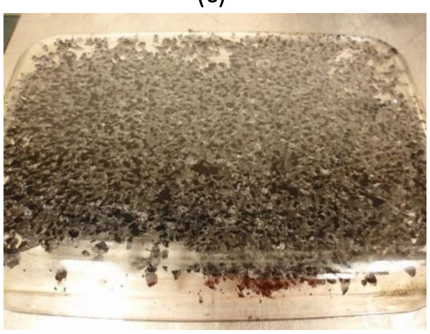

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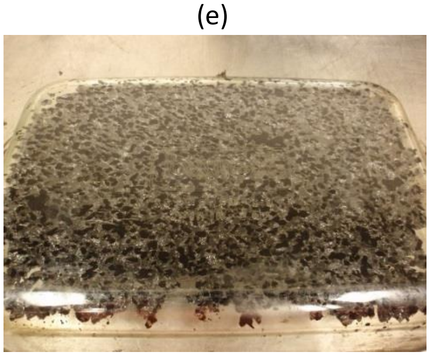

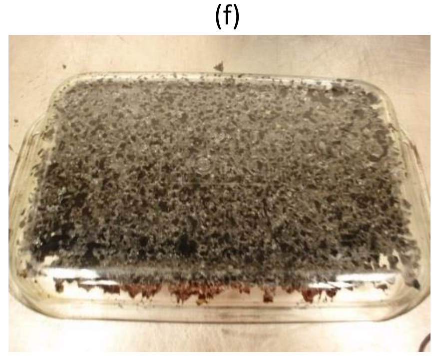

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Figure A.5 - PG 64-22 18.0% Passenger Car Ambient Rubber High Shear Optimum Binder Content (a) 6.0% - Specimen 1, (b) 6.0% - Specimen 2, (c) 6.5% - Specimen 1, (d) 6.5% - Specimen 2, (e) 7.0% - Specimen 2, (f) 7.0% - Specimen 2, (g) 7.5% - Specimen 1, (h) 7.5% - Specimen 2

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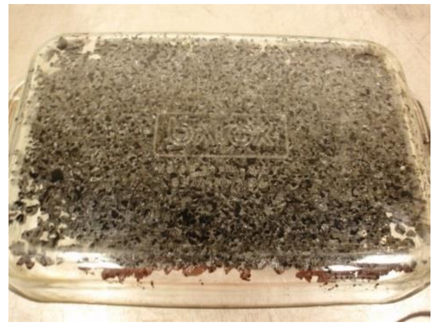

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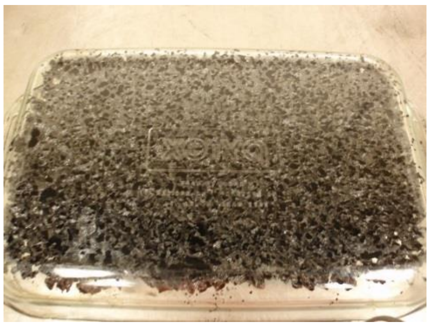

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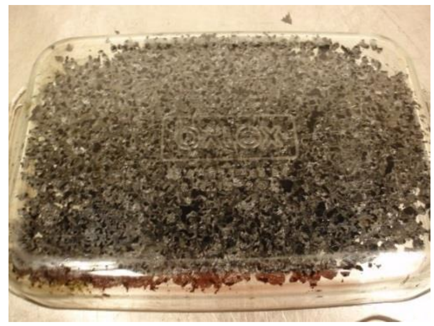

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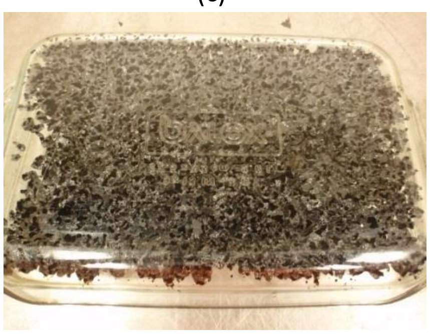

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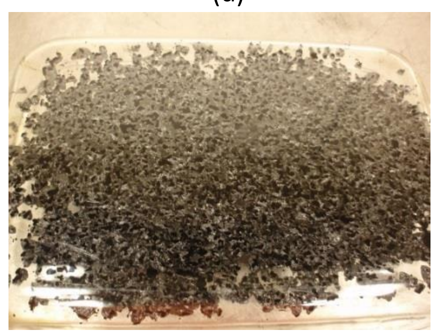

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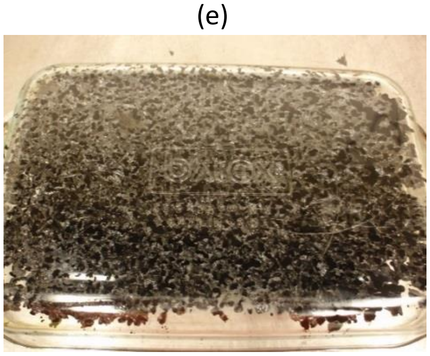

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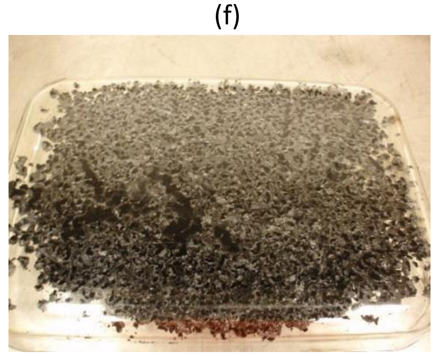
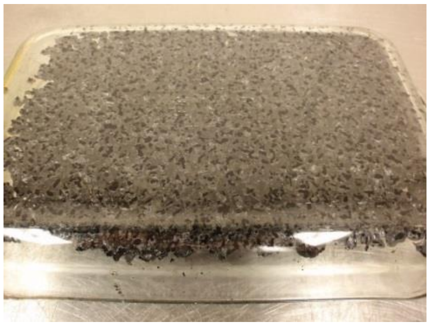


(h)

Figure A.6 - PG 64-22 16.0% Passenger Car Cryogenic Rubber High Shear Optimum Binder Content (a) 6.0% - Specimen 1, (b) 6.0% - Specimen 2, (c) 6.5% - Specimen 1, (d) 6.5% - Specimen 2, (e) 7.0% - Specimen 2, (f) 7.0% - Specimen 2, (g) 7.5% - Specimen 1, (h) 7.5% - Specimen 2



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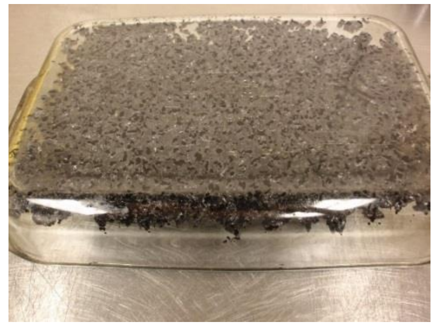

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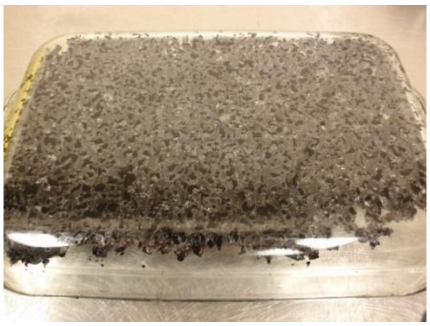

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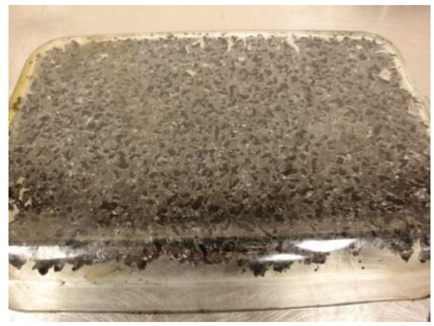

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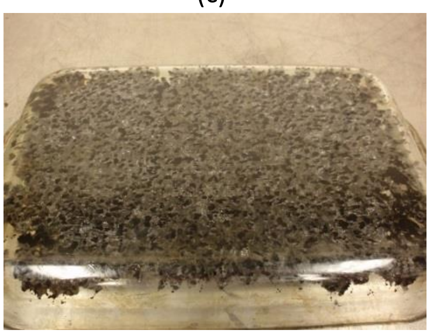

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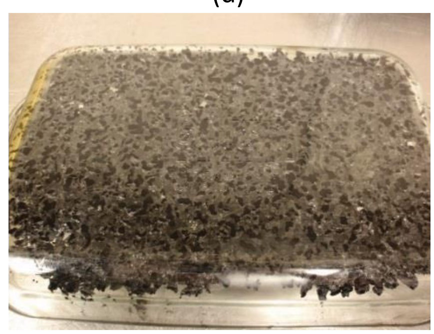

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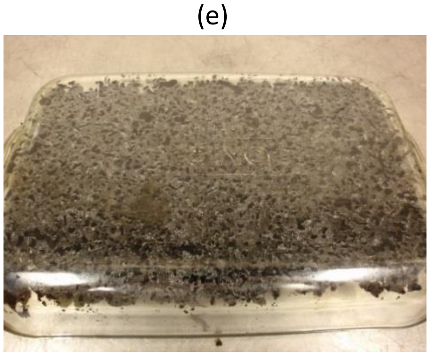

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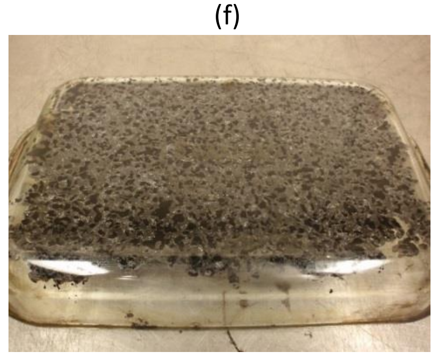
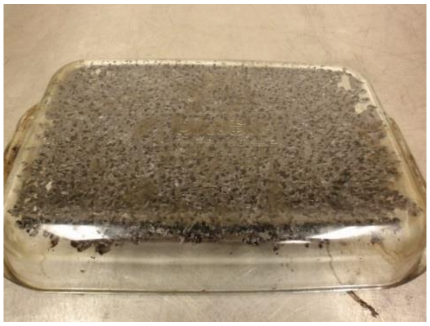
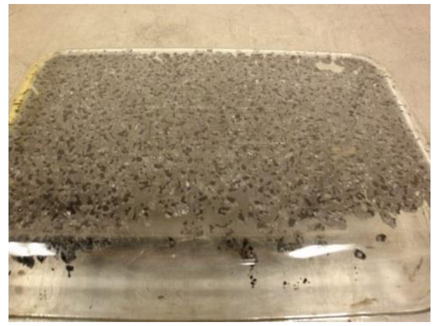


(h)

Figure A.7 - PG 64-22 15.5% Truck Tire Ambient Rubber High Shear Optimum Binder Content (a) 6.0% - Specimen 1, (b) 6.0% - Specimen 2, (c) 6.5% - Specimen 1, (d) 6.5% - Specimen 2, (e) 7.0% - Specimen 2, (f) 7.0% - Specimen 2, (g) 7.5% - Specimen 1, (h) 7.5% - Specimen 2



(a)



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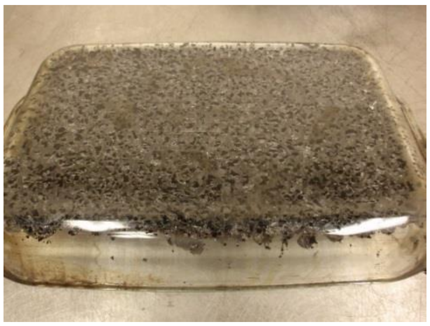

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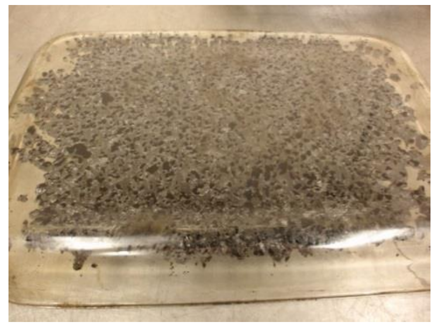

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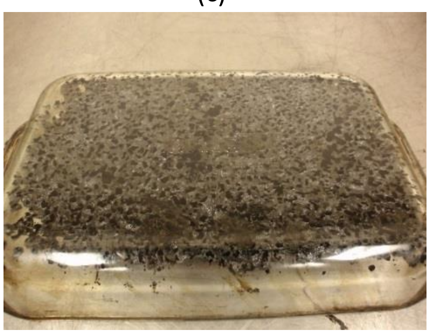
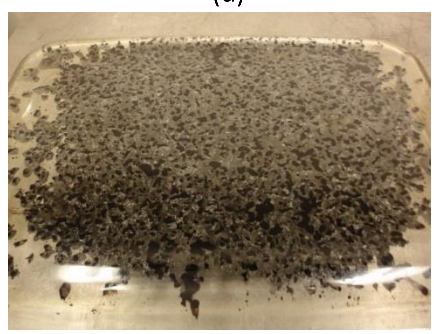


(e)



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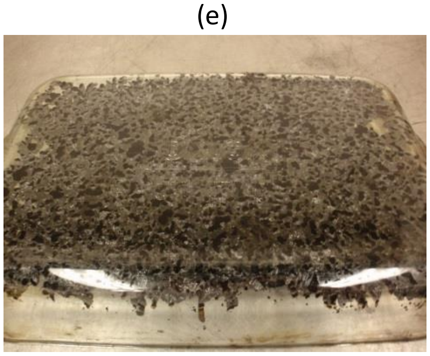
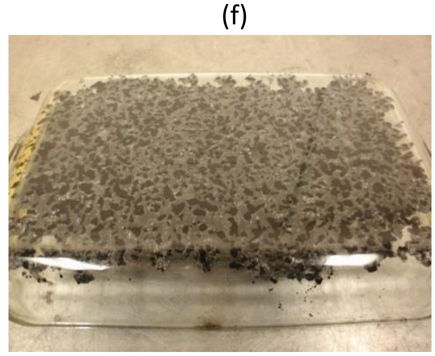
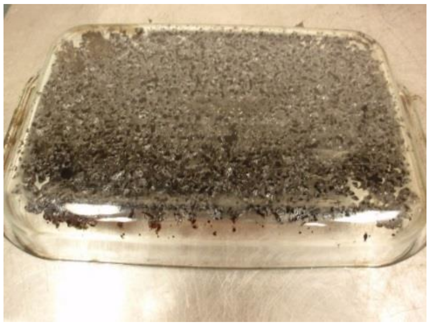


(g)



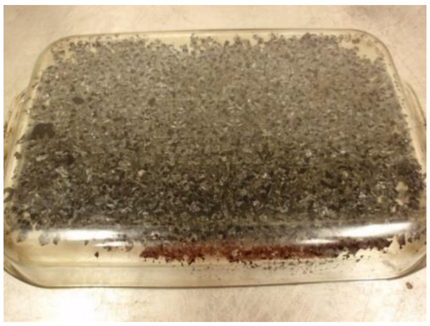
(h)

Figure A.8 - PG 64-22 16% Truck Tire Ambient Rubber Low Shear Optimum Binder Content (a) 6.0% - Specimen 1, (b) 6.0% - Specimen 2, (c) 6.5% - Specimen 1, (d) 6.5% - Specimen 2, (e) 7.0% - Specimen 2, (f) 7.0% - Specimen 2, (g) 7.5% - Specimen 1, (h) 7.5% - Specimen 2



(a)

(b)



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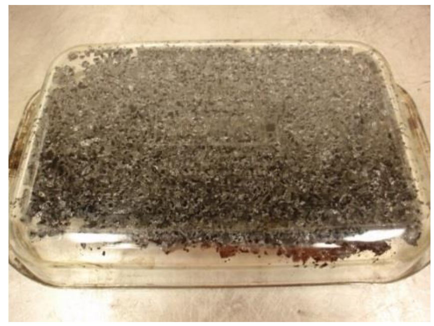
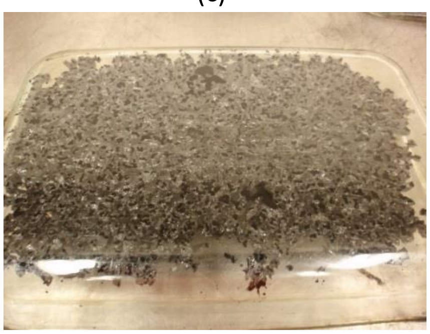


(d)



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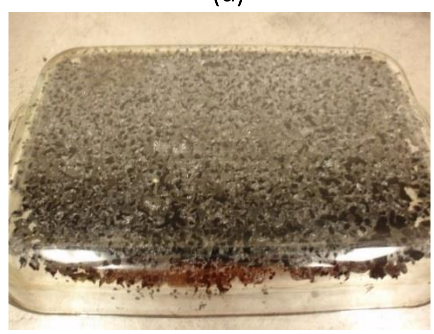
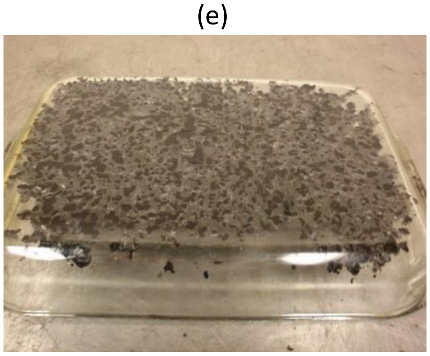
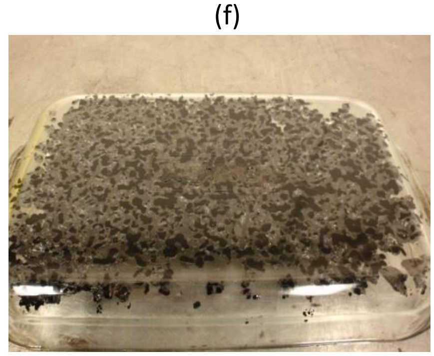


(f)



(g)



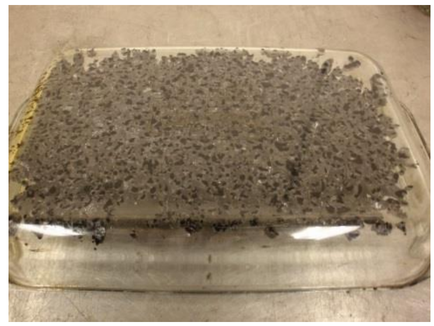
(h)

Figure A.9 - PG 64-22 16% Truck Tire Cryogenic Rubber Low Shear Optimum Binder Content (a) 6.0% - Specimen 1, (b) 6.0% - Specimen 2, (c) 6.5% - Specimen 1, (d) 6.5% - Specimen 2, (e) 7.0% - Specimen 2, (f) 7.0% - Specimen 2, (g) 7.5% - Specimen 1, (h) 7.5% - Specimen 2

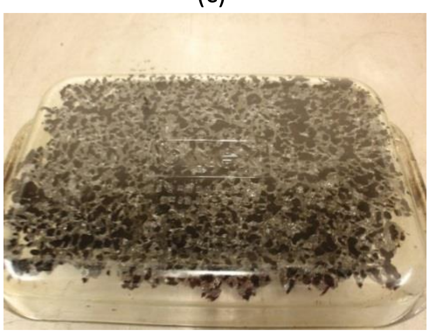
(a)

(b)

(c)



(d)



(e)

(f)

(g)

(h)

Figure A.10 - PG 64-22 15.5% Truck Tire Cryogenic Rubber High Shear Optimum Binder Content (a) 6.0% - Specimen 1, (b) 6.0% - Specimen 2, (c) 6.5% - Specimen 1, (d) 6.5% - Specimen 2, (e) 7.0% - Specimen 2, (f) 7.0% - Specimen 2, (g) 7.5% - Specimen 1, (h) 7.5% - Specimen 2

APPENDIX B

Draindown

Table B.1 – Draindown Data for Control Mixes

Mix	Specimen	Binder Content (%)	Draindown (%)		
			Hour 1	Hour 2	Hour 3
76-22	1	5.0	0.00	0.00	0.00
	2	5.0	0.00	0.00	0.00
	3	5.5	0.00	0.00	0.01
	4	5.5	0.00	0.00	0.00
	5	6.0	0.02	0.09	0.15
	6	6.0	0.02	0.11	0.16
76-22 With Fibers	1	7.0	0.00	0.00	0.00
	2	7.0	0.00	0.00	0.00
	3	7.5	0.01	0.01	0.01
	4	7.5	0.00	0.00	0.00
	5	8.0	0.00	0.01	0.01
	6	8.0	0.01	0.02	0.03

Table B.2 – Draindown Data for PC Amb Mixes

Mix	Specimen	Binder Content (%)	Draindown (%)		
			Hour 1	Hour 2	Hour 3
PC Amb Low	1	6.5	0.00	0.00	0.01
	2	6.5	0.00	0.00	0.00
	3	7.0	0.00	0.00	0.01
	4	7.0	0.00	0.00	0.00
	5	7.5	0.01	0.05	0.09
	6	7.5	0.01	0.01	0.02
PC Amb High	1	6.5	0.00	0.00	0.00
	2	6.5	0.00	0.00	0.00
	3	7.0	0.01	0.01	0.01
	4	7.0	0.00	0.00	0.00
	5	7.5	0.00	0.01	0.01
	6	7.5	0.01	0.02	0.03

Table B.3 – Draindown Data for PC Cryo Mixes

Mix	Specimen	Binder Content (%)	Draindown (%)		
			Hour 1	Hour 2	Hour 3
PC Cryo Low	1	6.5	0.00	0.00	0.00
	2	6.5	0.00	0.00	0.01
	3	7.0	0.01	0.01	0.02
	4	7.0	0.01	0.01	0.03
	5	7.5	0.01	0.02	0.02
	6	7.5	0.03	0.04	0.05
PC Cryo High	1	6.5	0.00	0.00	0.00
	2	6.5	0.00	0.00	0.00
	3	7.0	0.01	0.01	0.01
	4	7.0	0.00	0.00	0.01
	5	7.5	0.00	0.02	0.02
	6	7.5	0.00	0.02	0.02

Table B.4 – Draindown Data for TT Amb Mixes

Mix	Specimen	Binder Content (%)	Draindown (%)		
			Hour 1	Hour 2	Hour 3
TT Amb Low	1	6.5	0.00	0.00	0.00
	2	6.5	0.00	0.00	0.00
	3	7.0	0.00	0.00	0.00
	4	7.0	0.00	0.00	0.01
	5	7.5	0.00	0.00	0.00
	6	7.5	0.00	0.00	0.00
TT Amb High	1	6.5	0.01	0.01	0.01
	2	6.5	0.00	0.00	0.00
	3	7.0	0.00	0.00	0.02
	4	7.0	0.01	0.01	0.02
	5	7.5	0.00	0.00	0.05
	6	7.5	0.00	0.00	0.09

Table B.5 – Draindown Data for TT Cryo Mixes

Mix	Specimen	Binder Content (%)	Draindown (%)		
			Hour 1	Hour 2	Hour 3
TT Cryo Low	1	6.5	0.00	0.00	0.00
	2	6.5	0.00	0.00	0.01
	3	7.0	0.00	0.01	0.01
	4	7.0	0.00	0.00	0.01
	5	7.5	0.00	0.01	0.01
	6	7.5	0.01	0.02	0.02
TT Cryo High	1	6.5	0.00	0.00	0.00
	2	6.5	0.00	0.00	0.00
	3	7.0	0.00	0.01	0.02
	4	7.0	0.00	0.00	0.02
	5	7.5	0.00	0.02	0.04
	6	7.5	0.00	0.00	0.01

APPENDIX C

Porosity

Table C.1 – Porosity Data for Control Mixes

Mix	Specimen	Porosity (%)	Average Porosity (%)	Standard Deviation (%)
76-22	1	14.8	14.5	0.84
	2	15.4		
	3	14.7		
	4	13.3		
	5	14.1		
	6	15.2		
	7	13.4		
	8	13.9		
	9	13.7		
	10	14.4		
	11	16.3		
	12	14.5		
	13	15.5		
	14	14.2		
	15	14.5		
76-22 With Fibers	1	12.0	10.7	1.53
	2	15.1		
	3	11.3		
	4	9.3		
	5	10.7		
	6	9.8		
	7	10.5		
	8	9.5		
	9	10.4		
	10	10.7		
	11	8.9		
	12	12.3		
	13	10.4		
	14	10.3		
	15	9.7		

Table C.2 – Porosity Data for PC Amb Mixes

Mix	Specimen	Porosity (%)	Average Porosity (%)	Standard Deviation (%)
PC Amb Low	1	20.5	14.0	2.22
	2	13.8		
	3	14.9		
	4	12.7		
	5	13.0		
	6	15.0		
	7	14.3		
	8	13.6		
	9	11.5		
	10	12.1		
	11	15.8		
	12	12.1		
	13	14.7		
	14	13.0		
	15	12.2		
PC Amb High	1	13.5	12.2	0.75
	2	12.3		
	3	12.3		
	4	11.5		
	5	11.6		
	6	11.2		
	7	11.9		
	8	12.2		
	9	11.5		
	10	12.1		
	11	13.3		
	12	11.5		
	13	11.9		
	14	13.5		
	15	12.9		

Table C.3 – Porosity Data for PC Cryo Mixes

Mix	Specimen	Porosity (%)	Average Porosity (%)	Standard Deviation (%)
PC Cryo Low	1	10.5	10.6	0.67
	2	11.1		
	3	9.3		
	4	11.3		
	5	9.4		
	6	10.8		
	7	11.2		
	8	11.0		
	9	10.8		
	10	10.0		
	11	11.1		
	12	9.9		
	13	11.3		
	14	10.5		
	15	11.1		
PC Cryo High	1	10.0	12.3	2.35
	2	12.6		
	3	14.0		
	4	12.8		
	5	10.4		
	6	11.9		
	7	17.0		
	8	10.9		
	9	9.2		
	10	11.4		
	11	16.1		
	12	11.6		
	13	13.1		
	14	8.8		
	15	13.9		

Table C.4 – Porosity Data for TT Amb Mixes

Mix	Specimen	Porosity (%)	Average Porosity (%)	Standard Deviation (%)
TT Amb Low	1	19.9	17.3	1.60
	2	19.3		
	3	18.3		
	4	18.0		
	5	16.6		
	6	18.5		
	7	18.3		
	8	14.8		
	9	18.2		
	10	17.3		
	11	14.3		
	12	15.9		
	13	16.8		
	14	15.9		
	15	16.9		
TT Amb High	1	19.3	17.4	1.34
	2	20.8		
	3	17.4		
	4	17.7		
	5	16.9		
	6	16.9		
	7	16.8		
	8	17.3		
	9	18.6		
	10	17.1		
	11	16.8		
	12	17.0		
	13	16.2		
	14	16.2		
	15	15.5		

Table C.5 – Porosity Data for TT Cryo Mixes

Mix	Specimen	Porosity (%)	Average Porosity (%)	Standard Deviation (%)
TT Cryo Low	1	17.8	17.4	0.98
	2	19.1		
	3	17.1		
	4	18.7		
	5	18.6		
	6	15.8		
	7	17.0		
	8	16.7		
	9	16.8		
	10	17.2		
	11	18.1		
	12	17.6		
	13	17.3		
	14	15.7		
	15	17.1		
TT Cryo High	1	21.5	19.3	1.19
	2	21.4		
	3	20.0		
	4	20.3		
	5	18.3		
	6	18.9		
	7	18.0		
	8	18.5		
	9	20.4		
	10	18.4		
	11	18.5		
	12	18.0		
	13	18.5		
	14	18.7		
	15	19.5		

APPENDIX D

Permeability

Table D.1 – Permeability Data for Control Mixes

Mix	Specimen	Permeability (m/day)	Average Permeability (m/day)	Standard Deviation (m/day)
76-22	1	371.1	495.2	88.23
	2	470.9		
	3	462.8		
	4	506.0		
	5	551.4		
	6	554.9		
	7	381.6		
	8	393.8		
	9	616.7		
	10	474.3		
	11	510.6		
	12	647.5		
	13	378.1		
	14	517.4		
	15	590.5		
76-22 With Fibers	1	349.3	279	44.48
	2	262.0		
	3	243.2		
	4	316.8		
	5	344.6		
	6	269.7		
	7	250.1		
	8	278.0		
	9	267.0		
	10	328.2		
	11	176.9		
	12	255.7		
	13	302.2		
	14	283.9		
	15	258.2		

Table D.2 – Permeability Data for PC Amb Mixes

Mix	Specimen	Permeability (m/day)	Average Permeability (m/day)	Standard Deviation (m/day)
PC Amb Low	1	511.7	299.4	94.96
	2	175.9		
	3	494.4		
	4	269.6		
	5	303.0		
	6	309.9		
	7	284.8		
	8	228.9		
	9	282.6		
	10	237.8		
	11	388.1		
	12	248.6		
	13	260.0		
	14	235.5		
	15	260.2		
PC Amb High	1	351.3	280	77.61
	2	227.1		
	3	365.6		
	4	195.3		
	5	342.4		
	6	195.3		
	7	260.4		
	8	185.5		
	9	280.6		
	10	216.8		
	11	389.5		
	12	166.1		
	13	331.5		
	14	323.1		
	15	370.0		

Table D.3 – Permeability Data for PC Cryo Mixes

Mix	Specimen	Permeability (m/day)	Average Permeability (m/day)	Standard Deviation (m/day)
PC Cryo Low	1	296.9	276.7	49.1
	2	207.5		
	3	242.9		
	4	330.2		
	5	273.0		
	6	316.1		
	7	193.4		
	8	239.1		
	9	334.5		
	10	290.1		
	11	311.9		
	12	232.4		
	13	322.3		
	14	226.2		
	15	334.1		
PC Cryo High	1	205.6	263.7	70.72
	2	432.6		
	3	244.2		
	4	331.4		
	5	261.6		
	6	263.2		
	7	228.4		
	8	255.1		
	9	197.4		
	10	139.8		
	11	289.5		
	12	334.5		
	13	282.0		
	14	297.1		
	15	193.3		

Table D.4 – Permeability Data for TT Amb Mixes

Mix	Specimen	Permeability (m/day)	Average Permeability (m/day)	Standard Deviation (m/day)
TT Amb Low	1	367.8	12.9	309
	2	339.2		
	3	315.2		
	4	322.4		
	5	321.6		
	6	316.9		
	7	361.9		
	8	272.0		
	9	282.9		
	10	301.9		
	11	253.2		
	12	273.0		
	13	343.2		
	14	305.3		
	15	258.4		
TT Amb High	1	387.1	339.0	44.68
	2	444.9		
	3	346.8		
	4	351.7		
	5	312.1		
	6	324.6		
	7	362.3		
	8	340.7		
	9	381.4		
	10	301.6		
	11	274.4		
	12	313.5		
	13	301.2		
	14	357.9		
	15	285.0		

Table D.5 – Permeability Data for TT Cryo Mixes

Mix	Specimen	Permeability (m/day)	Average Permeability (m/day)	Standard Deviation (m/day)
TT Cryo Low	1	490.2	304.1	62.19
	2	283.0		
	3	308.0		
	4	288.5		
	5	294.9		
	6	272.3		
	7	273.2		
	8	249.6		
	9	302.0		
	10	288.4		
	11	381.9		
	12	327.7		
	13	264.6		
	14	230.9		
	15	305.8		
TT Cryo High	1	373.8	310.5	43.84
	2	362.4		
	3	325.0		
	4	351.2		
	5	264.0		
	6	315.1		
	7	230.1		
	8	284.0		
	9	320.1		
	10	267.4		
	11	333.8		
	12	264.0		
	13	293.9		
	14	373.3		
	15	299.1		

APPENDIX E

Long Term Draindown

Table E.1 – Aged Permeability for Control Mixes

Mix	Specimen	Aged Permeability (m/day)								
		Days at 60°C								
		0	14	28	42	56	70	84	98	112
76-22	4	506.0	523.0	355.3	344.8	347.4	401.3	391.2	384.7	366.5
	11	510.6	487.9	493.4	482.6	487.9	522.8	516.6	499.0	493.4
	14	517.4	500.0	489.0	478.5	473.4	393.8	386.9	408.2	432.0
76-22 With Fibers	3	243.2	281.6	244.6	176.1	171.9	171.2	169.8	166.5	164.6
	6	269.7	178.7	159.5	201.3	178.7	178.0	175.9	176.6	182.4
	15	258.2	325.1	210.0	189.2	184.4	183.6	183.6	181.4	188.4

Table E.2 – Aged Permeability for PC Amb Mixes

Mix	Specimen	Aged Permeability (m/day)								
		Days at 60°C								
		0	14	28	42	56	70	84	98	112
PC Amb Low	6	309.9	404.8	353.8	328.0	318.7	316.4	316.4	297.6	288.0
	8	228.9	388.3	275.2	295.8	236.3	232.6	230.1	227.7	223.0
	12	248.6	293.5	322.6	307.4	297.3	289.7	284.3	280.8	277.4
PC Amb High	9	280.6	339.3	334.2	321.9	310.5	299.8	299.8	291.8	286.1
	11	389.5	478.4	314.4	305.7	291.5	284.0	284.0	275.1	268.4
	13	331.5	384.3	339.2	305.8	319.3	245.3	241.2	229.7	227.3

Table E.3 – Aged Permeability for PC Cryo Mixes

Mix	Specimen	Aged Permeability (m/day)								
		Days at 60°C								
		0	14	28	42	56	70	84	98	112
PC Cryo Low	7	193.4	336.2	218.5	213.2	212.2	209.1	207.1	202.4	201.4
	12	232.4	284.6	238.7	226.5	224.2	219.8	217.6	206.5	201.8
	14	226.2	345.5	239.8	227.3	226.2	225.0	223.9	227.3	223.9
PC Cryo High	1	205.6	348.5	267.0	259.4	262.4	244.1	241.5	232.9	230.6
	3	244.2	357.3	268.5	268.5	265.2	260.4	258.9	254.3	242.9
	4	331.4	436.3	272.0	259.2	256.2	256.2	253.3	246.2	229.5

Table E.4 – Aged Permeability for TT Amb Mixes

Mix	Specimen	Aged Permeability (m/day)								
		Days at 60ºC								
		0	14	28	42	56	70	84	98	112
TT Amb Low	6	316.9	266.9	316.9	278.8	263.7	243.3	242.0	244.7	243.3
	13	343.2	333.1	264.5	295.8	308.0	297.8	295.8	310.1	305.9
	14	305.3	295.2	297.2	295.2	291.4	284.0	284.0	284.0	278.7
TT Amb High	6	324.6	288.3	256.2	244.8	243.4	242.1	240.8	225.9	224.7
	9	381.4	292.4	262.7	253.6	239.7	237.1	235.8	220.4	216.1
	13	301.2	287.7	299.2	270.4	265.6	262.4	262.4	245.2	237.5

Table E.5 – Aged Permeability for TT Cryo Mixes

Mix	Specimen	Aged Permeability (m/day)								
		Days at 60ºC								
		0	14	28	42	56	70	84	98	112
TT Cryo Low	3	308.0	348.3	308.0	283.0	290.2	288.4	283.0	277.8	272.8
	5	294.9	309.4	345.6	332.6	322.9	298.9	291.1	287.3	283.6
	8	249.6	298.2	298.2	304.1	306.2	300.2	300.2	296.3	292.5
TT Cryo High	9	320.1	302.0	299.9	317.7	313.1	313.1	310.8	282.2	274.9
	10	267.4	306.7	317.8	315.5	306.7	300.4	300.4	288.5	275.8
	13	293.9	339.8	327.1	304.2	317.5	304.2	302.1	290.0	282.5

APPENDIX F

Abrasion Loss

Table F.1 - Unaged Abrasion Loss Data for Control Mixes

Mix	Specimen	Loss (%)	Average Loss (%)	Standard Deviation (%)
76	7	14.4	15.5	2.50
	10	18.4		
	13	13.8		
76F	2	9.6	7.3	2.00
	8	6.7		
	11	5.7		

Table F.2 - Aged Abrasion Loss Data for Control Mixes

Mix	Specimen	Loss (%)	Average Loss (%)	Standard Deviation (%)
76	2	22.2	18.0	3.67
	9	16.5		
	12	15.3		
76F	4	10.0	8.5	1.38
	7	8.3		
	9	7.3		

Table F.3 - Unaged Abrasion Loss Data for PC Amb Mixes

Mix	Specimen	Loss (%)	Average Loss (%)	Standard Deviation (%)
PC Amb Low	10	12.8	12.0	1.17
	11	12.5		
	14	10.6		
PC Amb High	5	8.5	8.7	1.62
	7	7.2		
	14	10.4		

Table F.4 - Aged Abrasion Loss Data for PC Amb Mixes

Mix	Specimen	Loss (%)	Average Loss (%)	Standard Deviation (%)
PC Amb Low	1	16.2	14.5	1.49
	5	13.8		
	9	13.5		
PC Amb High	1	11.5	10.3	1.27
	2	10.4		
	6	9.0		

Table F.5 - Unaged Abrasion Loss Data for PC Cryo Mixes

Mix	Specimen	Loss (%)	Average Loss (%)	Standard Deviation (%)
PC Cryo Low	1	11.1	11.2	1.09
	9	12.4		
	13	10.2		
PC Cryo High	9	8.8	9.9	1.07
	10	10.0		
	11	11.0		

Table F.6 - Aged Abrasion Loss Data for PC Cryo Mixes

Mix	Specimen	Loss (%)	Average Loss (%)	Standard Deviation (%)
PC Cryo Low	3	13.5	12.3	1.16
	4	12.3		
	11	11.2		
PC Cryo High	6	13.2	11.3	1.82
	12	11.0		
	13	9.6		

Table F.7 - Unaged Abrasion Loss Data for TT Amb Mixes

Mix	Specimen	Loss (%)	Average Loss (%)	Standard Deviation (%)
TT Amb Low	2	16.7	12.3	3.78
	8	9.9		
	10	10.3		
TT Amb High	1	14.6	10.8	4.00
	7	11.0		
	11	6.6		

Table F.8 - Aged Abrasion Loss Data for TT Amb Mixes

Mix	Specimen	Loss (%)	Average Loss (%)	Standard Deviation (%)
TT Amb Low	1	17.4	13.5	3.39
	9	12.2		
	11	11.0		
TT Amb High	2	15.3	12.4	2.65
	14	12.0		
	15	10.1		

Table F.9 - Unaged Abrasion Loss Data for TT Cryo Mixes

Mix	Specimen	Loss (%)	Average Loss (%)	Standard Deviation (%)
TT Cryo Low	4	14.8	11.2	3.21
	6	8.6		
	10	10.3		
TT Cryo High	2	17.4	14.1	3.36
	5	14.3		
	8	10.7		

Table F.10 - Aged Abrasion Loss Data for TT Cryo Mixes

Mix	Specimen	Loss (%)	Average Loss (%)	Standard Deviation (%)
TT Cryo Low	2	15.6	15.2	2.31
	12	17.3		
	14	12.7		
TT Cryo High	1	20.6	15.0	5.22
	7	10.3		
	12	14.2		

APPENDIX G

Texas Overlay Test

Table H.1 – Texas Overlay Test Data of Unaged Specimens

Mix	Specimen	Percent Reduction (%)	Average Percent Reduction (%)	Standard Deviation (%)
76	6	79.5	86.1	5.81
	8	90.0		
	15	89.0		
76F	5	80.0	79.0	1.45
	13	79.6		
	14	77.3		
PC Amb Low	2	86.1	84.5	2.41
	3	85.7		
	15	81.7		
PC Amb High	4	83.0	83.5	6.82
	8	77.0		
	15	90.6		
PC Cryo Low	2	69.1	72.2	2.84
	8	72.7		
	10	74.8		
PC Cryo High	2	90.6	83.6	6.11
	5	80.8		
	15	79.4		
TT Amb Low	3	79.6	84.3	4.54
	4	84.8		
	12	88.6		
TT Amb High	4	78.6	79.8	5.19
	10	85.5		
	12	75.3		
TT Cryo Low	9	85.7	90.0	3.86
	11	91.4		
	13	93.0		
TT Cryo High	4	84.2	88.4	3.65
	6	89.9		
	14	91.0		

Table H.2 – Texas Overlay Test Data of Aged Specimens

Mix	Specimen	Percent Reduction (%)	Average Percent Reduction (%)	Standard Deviation (%)
76	1	79.6	82.9	3.21
	3	83.3		
	5	86.0		
76F	1	82.3	80.2	1.93
	10	79.6		
	12	78.6		
PC Amb Low	4	70.8	77.1	10.60
	7	71.2		
	13	89.4		
PC Amb High	2	81.5	80.9	1.13
	10	79.6		
	12	81.5		
PC Cryo Low	5	86.2	81.3	4.70
	6	80.8		
	15	76.8		
PC Cryo High	7	89.2	87.9	1.09
	8	87.2		
	12	87.5		
TT Amb Low	7	82.4	85.0	2.83
	5	84.7		
	15	88.0		
TT Amb High	3	93.1	87.3	5.56
	5	82.0		
	8	87.0		
TT Cryo Low	1	88.8	87.7	1.60
	7	85.9		
	15	88.5		
TT Cryo High	3	83.2	81.0	3.73
	11	76.7		
	15	83.0		

Table H.3 – Texas Overlay Test Slope Data from 0-10 Cycles of Unaged Specimens

Mix	Specimen	Slope	Average Slope	Standard Deviation
76	6	4.0	4.0	0.94
	8	4.9		
	15	3.0		
76F	5	4.2	4.2	0.07
	13	4.2		
	14	4.1		
PC Amb Low	2	4.0	4.1	0.09
	3	4.2		
	15	4.0		
PC Amb High	4	3.6	3.7	0.40
	8	3.4		
	15	4.2		
PC Cryo Low	2	3.3	3.4	0.17
	8	3.6		
	10	3.5		
PC Cryo High	2	4.1	3.8	0.25
	5	3.6		
	15	3.7		
TT Amb Low	3	3.8	3.8	0.14
	4	3.9		
	12	3.7		
TT Amb High	4	3.7	3.8	0.38
	10	4.2		
	12	3.5		
TT Cryo Low	9	3.5	3.8	0.28
	11	4.1		
	13	3.7		
TT Cryo High	4	3.3	3.4	0.17
	6	3.6		
	14	3.5		

Table H.4 – Texas Overlay Test Slope Data from 0-10 Cycles of Aged Specimens

Mix	Specimen	Slope	Average Slope	Standard Deviation
76	1	3.9	4.0	0.09
	3	4.0		
	5	4.1		
76F	1	4.3	4.2	0.15
	10	4.1		
	12	4.1		
PC Amb Low	4	0.0	2.5	2.21
	7	3.6		
	13	4.0		
PC Amb High	2	4.1	3.8	0.43
	10	3.3		
	12	4.0		
PC Cryo Low	5	4.4	3.9	0.43
	6	3.7		
	15	3.7		
PC Cryo High	7	3.6	3.9	0.45
	8	4.4		
	12	3.7		
TT Amb Low	7	3.6	4.0	0.38
	5	4.3		
	15	4.1		
TT Amb High	3	4.6	4.0	0.59
	5	3.5		
	8	4.0		
TT Cryo Low	1	3.7	3.6	0.15
	7	3.5		
	15	3.5		
TT Cryo High	3	4.4	3.9	0.43
	11	3.7		
	15	3.7		

Table H.5 – Texas Overlay Test Slope Data from 400-1200 Cycles of Unaged Specimens

Mix	Specimen	Slope	Average Slope	Standard Deviation
76	6	0.0077	0.0061	0.00276
	8	0.0029		
	15	0.0076		
76F	5	0.0065	0.0061	0.00030
	13	0.0059		
	14	0.0060		
PC Amb Low	2	0.0060	0.0068	0.00071
	3	0.0070		
	15	0.0073		
PC Amb High	4	0.0119	0.0126	0.00062
	8	0.0130		
	15	0.0129		
PC Cryo Low	2	0.0095	0.0091	0.00038
	8	0.0087		
	10	0.0091		
PC Cryo High	2	0.0079	0.0095	0.00236
	5	0.0085		
	15	0.0122		
TT Amb Low	3	0.0088	0.0074	0.00343
	4	0.0099		
	12	0.0035		
TT Amb High	4	0.0088	0.0085	0.00095
	10	0.0074		
	12	0.0092		
TT Cryo Low	9	0.0064	0.0101	0.00421
	11	0.0094		
	13	0.0147		
TT Cryo High	4	0.0170	0.0153	0.00163
	6	0.0151		
	14	0.0137		

Table H.6 – Texas Overlay Test Slope Data from 400-1200 Cycles of Aged Specimens

Mix	Specimen	Slope	Average Slope	Standard Deviation
76	1	0.0070	0.0074	0.00037
	3	0.0076		
	5	0.0076		
76F	1	0.0067	0.0067	0.00019
	10	0.0069		
	12	0.0066		
PC Amb Low	4	0.0000	0.0047	0.00418
	7	0.0081		
	13	0.0060		
PC Amb High	2	0.0076	0.0089	0.00162
	10	0.0107		
	12	0.0085		
PC Cryo Low	5	0.0060	0.0075	0.00146
	6	0.0089		
	15	0.0077		
PC Cryo High	7	0.0156	0.0108	0.00420
	8	0.0086		
	12	0.0081		
TT Amb Low	7	0.0100	0.0085	0.00202
	5	0.0062		
	15	0.0093		
TT Amb High	3	0.0095	0.0091	0.00062
	5	0.0093		
	8	0.0084		
TT Cryo Low	1	0.0102	0.0079	0.00200
	7	0.0071		
	15	0.0064		
TT Cryo High	3	0.0075	0.0113	0.00369
	11	0.0115		
	15	0.0149		

APPENDIX H

Dynamic Modulus

Table H.1 – Dynamic Modulus Data for Control Mixes

Test Temperature (°C)	Mix	Specimen	Dynamic Modulus (MPa) Frequency (Hz) 10	1	0.1	0.01
4	76-22	DM-1	7781	5736	3865	-
		DM-2	8775	6550	4481	-
		DM-3	8080	5882	3920	-
	76 With Fibers	DM-1	8096	5947	3972	-
		DM-2	8761	6486	4383	-
		DM-3	8869	6434	4296	-
20	76-22	DM-1	3915	2250	1152	-
		DM-2	4163	2419	1281	-
		DM-3	3907	2240	1148	-
	76 With Fibers	DM-1	3528	1951	962	-
		DM-2	4185	2415	1253	-
		DM-3	4214	2419	1245	-
45	76-22	DM-1	769	279	115	57
		DM-2	827	324	153	82
		DM-3	701	261	111	59
	76 With Fibers	DM-1	535	184	79	46
		DM-2	772	299	134	73
		DM-3	655	240	99	51

Table H.2 – Dynamic Modulus Data for PC Amb Mixes

Test Temperature (°C)	Mix	Specimen	Dynamic Modulus (MPa) Frequency (Hz) 10	1	0.1	0.01
4	PC Amb Low	DM-1	7959	5909	4029	-
		DM-2	6963	5132	3465	-
		DM-3	8099	5948	4047	-
	PC Amb High	DM-1	7214	5199	3431	-
		DM-2	6246	4559	3073	-
		DM-3	6761	4874	3185	-
20	PC Amb Low	DM-1	4009	2367	1251	-
		DM-2	3463	1989	1023	-
		DM-3	4043	2387	1255	-
	PC Amb High	DM-1	3644	2069	1036	-
		DM-2	3033	1675	835	-
		DM-3	3092	1722	842	-
45	PC Amb Low	DM-1	642	218	80	32
		DM-2	520	173	66	28
		DM-3	852	323	121	43
	PC Amb High	DM-1	581	190	71	29
		DM-2	494	161	58	24
		DM-3	448	142	42	24

Table H.3 – Dynamic Modulus Data for PC Cryo Mixes

Test Temperature (°C)	Mix	Specimen	Dynamic Modulus (MPa) Frequency (Hz) 10	1	0.1	0.01
4	PC Cryo Low	DM-1	6637	4987	3466	-
		DM-2	7409	5426	3671	-
		DM-3	6386	4857	3362	-
	PC Cryo High	DM-1	7753	5746	3887	-
		DM-2	7798	5838	4037	-
		DM-3	7221	5265	3522	-
20	PC Cryo Low	DM-1	3418	2020	1062	-
		DM-2	3551	2061	1058	-
		DM-3	3383	1980	1035	-
	PC Cryo High	DM-1	3706	2144	1091	-
		DM-2	3894	2320	1229	-
		DM-3	3602	2087	1071	-
45	PC Cryo Low	DM-1	561	191	67	26
		DM-2	544	179	65	26
		DM-3	541	181	65	26
	PC Cryo High	DM-1	567	186	65	24
		DM-2	651	214	76	22
		DM-3	566	194	72	29

Table H.4 – Dynamic Modulus Data for TT Amb Mixes

Test Temperature (°C)	Mix	Specimen	Dynamic Modulus (MPa)			
			Frequency (Hz)			
			10	1	0.1	0.01
4	TT Amb Low	DM-1	5498	3762	2366	-
		DM-2	6116	4426	2940	-
		DM-3	7047	5204	3565	-
	TT Amb High	DM-1	6898	5029	3381	-
		DM-2	7832	5806	3993	-
		DM-3	6518	4759	3210	-
20	TT Amb Low	DM-1	2676	1491	746	-
		DM-2	3001	1529	772	-
		DM-3	3629	2166	1179	-
	TT Amb High	DM-1	3574	2104	1106	-
		DM-2	3830	2289	1237	-
		DM-3	3252	1895	976	-
45	TT Amb Low	DM-1	470	163	64	29
		DM-2	530	183	68	29
		DM-3	758	289	116	50
	TT Amb High	DM-1	543	179	66	29
		DM-2	746	279	113	45
		DM-3	508	169	63	26

Table H.5 – Dynamic Modulus Data for TT Cryo Mixes

Test Temperature (°C)	Mix	Specimen	Dynamic Modulus (MPa) Frequency (Hz) 10	1	0.1	0.01
4	TT Cryo Low	DM-1	8149	6230	4396	-
		DM-2	6574	4896	3397	-
		DM-3	7373	5572	3893	-
	TT Cryo High	DM-1	7284	5469	3793	-
		DM-2	7791	5774	3955	-
		DM-3	7006	5177	3550	-
20	TT Cryo Low	DM-1	4306	2590	1402	-
		DM-2	3355	1986	1038	-
		DM-3	3797	2270	1194	-
	TT Cryo High	DM-1	3485	2029	1075	-
		DM-2	3895	2292	1206	-
		DM-3	3676	2180	1162	-
45	TT Cryo Low	DM-1	804	285	100	39
		DM-2	561	187	63	24
		DM-3	640	211	71	26
	TT Cryo High	DM-1	647	229	86	34
		DM-2	616	211	78	32
		DM-3	621	213	77	30

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